Predicting the Effect of Variability on the Efficiency of Flow processing Systems

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Abstract

Manufacturing organisations are continually facing challenges through the action of competitive market pressures. Currently such organisations aim to gain competitive advantage by offering wider ranges of products, shorter lead times, increased delivery reliability and costs reductions on a year-by-year basis. In order to achieve this aim flow processing systems are increasingly being adopted, by a wider range of industrial sectors, as part of an overall lean manufacturing approach. As a result the levels of product and process variability that flow processing systems need to effectively contend with are significantly increasing.

The current research has, therefore, investigated the effects of variability on flow processing lines with the overall aim of enabling suitable methods, to be selected, for maintaining flow processing efficiency. In achieving this aim a detailed examination of both flow processing and variability has been undertaken. In the case of the later area the research has identified the various causes and types of variability on flow processing lines. A novel method has been developed for categorising sources of variability that can be used to decide appropriate methods of overcoming its unfavourable effects.

Through a review of the research literature the potential effect of variability on flow processing efficiency has been examined. This research has been found to be limited in

terms of the length of flow processing lines and the range of flow line characteristics examined. This research, therefore, identified a lack of suitable methods for quantitatively measuring both the variability levels associated with individual work stations and the effects of such variability on the overall flow processing line. Methods have, therefore, been developed, during this research, in order to fill these gaps, i.e. methods have been developed for:

1. *Generating variability probability distributions for individual work tasks within a work station and combining these distributions into a single variability probability distribution for a work station.*
2. *Using these workstation variability measurements to determine their effects on the utilisation of individual workstation's within the flow line.*

Using the methods developed estimates can be obtained for the % blocking and % waiting arising on individual work stations within a flow line due to variability. Using these estimates it is then possible to decide appropriate methods for resolving efficiency issues resulting from this variability.

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Declaration

I declare that the work described within this thesis was originally undertaken by myself, (Riham Khalil) between the dates of registration for the degree of Doctor of Philosophy at De Montfort University, September 2001 to May 2005.

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Abbreviations and Glossary

% Waiting	It is the waiting time for succeeding workstation, is waiting for the preceeding workstation to finish the jobs.
%Blocking	It is the waiting time for preceding machine is waiting for the succeeding workstation to finish the jobs.
BFC	Bottleneck Flow Control
COV	The coefficient of variation measures the spread of a set of data as a proportion of its mean. It is often expressed as a percentage
DFC	Dynamic Flow Control
ERP	Enterprise Resource Planning
GT	Group technology
HDV	High Demand Volume
LDV	Low Demand Volume
LPV	Low Product Variety
Mean	The mean is a particularly informative measure of the "central tendency" of the variable if it is reported along with its confidence intervals.
Median	The median is the value halfway through the ordered data set, below and above which there lies an equal number of data values.
MRP	Material Requirements Planning
OFC	Output Flow Control
PERT	Program Evaluation Review Technique
RPW	Rank Positional Weight
SD	Standard deviation is a measure of the spread or dispersion of a set of data.

Skewness	Skewness is defined as asymmetry in the distribution of the sample data values. Values on one side of the distribution tend to be further from the 'middle' than values on the other side.
SMED	Single Minute Exchange of Dies
TAKT	TAKT is a German term for rhythm. TAKT time is the allowable time to produce one product at the rate customers are demanding it. This is NOT the same as cycle time, which is the normal time to complete an operation on a product (which should be less than or equal to TAKT time).
TPM	Total Protective Maintenance
TQM	Total Quality Management

Notation

$\% B_{1,n}$	= %Blocking of the 1st workstation on an *n* workstation line
$\% B_{i,n}$	= %Blocking of the *i*th workstation of a flow line *n* workstations in length
$\% B_{n-1,n}$	= %Blocking of the 1st workstation on *n* workstation on line
$\%B_{1,2}$	= %Blocking on the 1st Workstation of a 2-workstation flow line
$\%W_{2,2}$	= %Waiting on the 2nd Workstation of a 2-workstation flow line
A	= Workstation availability resulting from the occurrence of stoppages caused by such activities as changeovers, equipment breakdowns and planned maintenance
a_{SSTBO}	= the shortest likely time between occurrences of short stoppages
a_{ECT_SS}	= the shortest likely effective task cycle time resulting from the effect of short stoppages
$a_{ECT\_SS\&LS}$	= the shortest likely effective task cycle time resulting from the combined effects of long and short stoppages
a_i	= $a_{ECT\_SS\&LS}$ for task *i*
a_{LSA}	= least level of availability resulting from the occurrence of long stoppages
a_{LSD}	= the shortest likely time durations of long stoppages
a_{SSA}	= least level of availability resulting from the occurrence of short stoppages
a_{SSD}	= the shortest likely time duration of a short stoppage
a_{TCT}	= shortest likely time required to complete a task
a_{WS}	= the shortest effective workstation cycle time

b_{SSTBO} = the longest likely time between occurrences of short stoppages

b_{ECT_SS} = the longest likely effective task cycle time resulting from the effect of short stoppages

$b_{ECT\_SS\&LS}$ = the longest likely effective task cycle time resulting from the combined effects of long and short stoppages

b_i = $b_{ECT\_SS\&LS}$ for task i

b_{LSA} = largest level of availability resulting from the occurrence of long stoppages

b_{LSD} = the longest likely time durations of long stoppages

b_{SSA} = greatest level of availability resulting from the occurrence of short stoppages

b_{SSD} = the longest likely time duration of a short stoppage

b_{TCT} = longest likely time required to complete a task

b_{WS} = the longest effective workstation cycle times

$C_{1,n}$ = Value of the constant calculated in Equation 24

$Cf_{1,n}$ = Value of the coefficient calculated in Equation 25

$Cf_{n-1,n}$ = Value of coefficient calculated in Equation 28

$C_{n-1,n}$ = Value of constant calculated in Equation 27

$CV_{1,2}$ = Coefficient of variation of the 1st Workstation of a 2-workstation flow line

i = Position of workstation in the line

m_f = Mean time between occurrence of stoppages, i.e. number per time period

m_r = Mean stoppage time

n = number of individual tasks allocated to the workstation

n = Number of workstations on the line

$rPM_{1,2}$ = The ratio of the 2nd to 1st the workstation PERT means

S = Rate of change of %Blocking between workstations, i.e. the slope such activities as changeovers, equipment breakdowns and planned maintenance

t_{SSTBO} = the most likely time between occurrences of short stoppages

t_{ECT_SS} = the most likely effective task cycle time resulting from the effect of short stoppages

$t_{ECT\_SS\&LS}$ = the most likely effective task cycle time resulting from the combined effects of long and short stoppages

t_i = $t_{ECT\_SS\&LS}$ for task *i*

t_{LSA} = most likely level of availability resulting from the occurrence of long stoppages

t_{LSD} = the most likely time durations of long stoppages

t_{SSA} = most likely level of availability resulting from the occurrence of short stoppages

t_{SSD} = the most likely time duration of a short stoppage

t_{TCT} = most likely time required to complete a task

t_{WS} = the most likely effective workstation cycle times

Chapter 1 Introduction

1.1 Manufacturing Competitiveness

Over the last decade the competitive environment of manufacturing enterprises has changed considerably (Stalk and Hout, 1992). An initial emphasis on *quality* became the baseline from which to compete since high levels of quality quickly became taken for granted by customers. The focus of competitive attention then became those of reducing delivery lead time and improving delivery reliability (Sun et al. 2005). In more recent years the provision of increasing levels of product choice and continuous reductions in costs have been added to the competitive mix. There is now increasing pressure on suppliers to provide higher levels of cost, quality and delivery performance in addition to ensuring the availability of a wider choice of products.

An essential methodology, increasingly being adopted by manufacturing organisations, that is capable of assisting manufacturing organisations in fulfilling these competitive demands is that of lean production which has been shown to provide (Monden 1983, Womack, Jones and Roos 1990, Smeds 1990, Yusuf 2002) significant advantages in the critical areas of:

- **a.** shortening lead times,
- **b.** improving delivery reliability,
- **c.** reducing costs,
- **d.** improving quality, and
- **e.** widening product mixes.

Studies have shown that organisations making use of lean production techniques tend to have significant performance advantages over conventionally organised plants (Smeds 1990, Schonberger 1992, Chappell 2002). There is also research that has reported the limitations of the lean philosophy, most notably Burgelman, (1983), who argues that environmental and social conditions have not been taken fully into consideration in explaining the use of lean production in Japan's competitive advantage. However, it is generally accepted that lean manufacturing practices have the ability to provide improvements in the majority of those areas considered critical to the competitiveness of an organisation.

1.2 Lean Implementation Process

The basic process steps involved in the implementation of lean production (Womack, Jones and Roos 1990, Haque and Moore 2004) are:

i. **Listening to the voice of the customer** in order to ensure the precise definition of customer's needs and the successful conversion of these needs into operational activities.

ii. **Mapping the value stream,** i.e. identifying the sequence of added-value activities that are required to convert raw materials to finished goods.

iii. **Implementing flow processing** through the sequential layout of processing equipment according to the needs of the product and the balancing of work loads at workstations along the flow line.

iv. **Implementing pull material control** which ensures that the production system is synchronised to customer demands, i.e. produces only what the customer wants when it is wanted. A major barrier to the implementation of pull systems is a lack of regularity in the flow of materials through the manufacturing system (Karmarkar, Kerke and Sham 1989).

v. **Seeking perfection through continuous improvement** the main focus of which is to remove or reduce the sources of variability that prevent smooth material flow through the flow processing line (Imai 1986).

Of the above list it can be seen that the implementation of flow processing is essential to the lean production philosophy since it provides the infrastructure for both pull production to take place and the elimination of waste. In addition, of these basic lean steps implementing flow processing is perhaps the most difficult to achieve since it often requires a radical redesign in the methods of working to provide the basis for material flow.

1.3 Application of Lean to High Product Variety/Low Demand Volume Environments

With its emphasis on the use of flow processes, lean practices have primarily been restricted to applications within high demand volume/low product variety (HDV/LPV) manufacturing environments such as the automotive industry. Only in these environments could the introduction of flow processing be successfully achieved. The growth in recent years of lean practices outside the automotive sector was also largely confined to those industrial environments dealing with high volume and low product variety.

Such is the success of lean practices that low demand volume/ high product variety (LDV/HPV) industrial sectors, such as the aerospace industry, are committing huge amounts of resources to introducing such practices within their traditional LDV/HPV manufacturing environments. Prominent lean manufacturing programmes aimed at LDV/HPV manufacturing environments include the UK and US Lean Aerospace Initiatives (Levantesi 2000) and Airbus UK (Anonymous 2003).

Several implementations of LDV/HPV flow processing lines currently in use within industry include Caterpillar (Anonymous 2002) and Rolls-Royce (Anonymous 2003). These systems tend to use long TAKT times, i.e. 40 minutes in the case of Caterpillar BCP and approximately 14 hours in the case of Rolls-Royce and Airbus UK. It is expected, that as knowledge and experience of applying lean practices within such systems is gained then their use will grow in both LDV/HPV environments and HDV/LPV environments where the demand from customers for wider product choice may prevent the use of traditional single product, short-TAKT flow processing systems.

The introduction of flow processing systems within LDV/HPV manufacturing environments has been a major research challenge for several decades. Notable successes include Group Technology (Snead 1989) and Cellular Manufacturing (Chen 2003). However, these methodologies merely apply flow processing to isolated pockets of HDV/LPV work that may exist within larger LDV/HPV environments. Hence these methods are essentially HDV/LPV flow processing systems. These methods do not address the issues of implementing flow within LDV/HPV situations. Recently there have been attempts at achieving this latter aim reported in the literature. For example, Stockton and Lindley (1998) developed a computer based simulation study, using the Promodel (Harrell et. al. 1992) software, the objectives of which were to study the operational behaviour of Process Sequence Cell Layouts in order to gain insights into their dynamic characteristics. Of interest was the behaviour of the material flows between cells under alternative conditions, namely varying levels of component variety, number of batches, and alternative batch sizes.

The use of flow processing into a wider range of production environments results in the need, therefore, for this type of system to operate under a wider range of conditions particularly with respect to the levels of variability that exist and range of sources of such variability.

Within LDV/HPV flow processing systems there is a lack of understanding of the inter-actions between the various sources of variation and of their cumulative effects on overall efficiency of flow processing systems.

1.4 Aims and Objectives of Research

Greater levels of product and process variability are rapidly becoming an inherent part of the environment under which flow processing lines must operate. Changes in the manufacturing environment responsible for these increased levels of variability include:

a. increased levels of product choice and customisation of products with a consequent reduction in demand volumes,

b. increased implementation of lean practices with in high product variety/low demand volume manufacturing environments where flow processing is an essential part of lean implementations, and

c. greatly increased Takt times leading to such activities as set-ups, planned maintenance and equipment breakdowns taking place within the normal flow process line operating periods.

The overall effect of this variability is to drastically reduce flow process line efficiency leading to reduced throughput rates and inefficient use of labour and equipment resources. The **aim of the current research,** therefore, is to enable high variability flow lines to operate more effectively through enabling the improved use of methods that can help to overcome the detrimental effects of this variability. These methods include line balancing, part sequencing, continuous improvement techniques, variability pooling and flexible resources. Their improved use requires knowledge of:

a. the levels of time variability inherent in individual work tasks,
b. the levels of time variability inherent in individual workstations, and
c. the effects that differences in workstation variability have on individual resource utilisations of workstations.

The **research objectives** are, therefore, to examine methods by which the above knowledge may be obtained. Achieving these research objectives focuses on the need to develop methods for quantitatively measuring the levels of *blocking* and *waiting* that arise within individual workstations as a result of variability.

1.5 Structure of the Thesis

As a first step to achieving the research objectives Chapter 2 addresses the subject of flow processing and begins by providing details of the generic characteristics of such systems. From these characteristics it is clear that activities, such as set-ups and planned maintenance operations, which cause interruptions in the smooth flow of materials through flow processing lines are assumed to occur outside the normal production time. In addition, these characteristics also emphasise the need for high levels of process reliability and process capability to avoid interruptions within production time resulting from equipment breakdowns and quality defects, and also the use of standardised work methods to reduce levels of task time variability.

Cellular manufacturing is identified, in Chapter 2, as the primary method by which flow processing has been introduced into high product variety/low demand volume manufacturing environments. However, the success of this methodology is identified has being based on the application of methods for reducing the levels of variation individual manufacturing cells need to cope with. Traditional methods of designing such systems are found to rely on the assumption that task times are deterministic not stochastic.

Chapter 2 then identifies the limitations of existing approaches to flow line design when variability exists and identifies the importance of ensuring that workstations can start and end TAKT cycles in a synchronised manner. Also, in Chapter 2, the causes of time variability within flow processing lines are examined and found to be related to variability in time consuming activities and the resources required for performing these activities.

Chapter 3 then reviews the subject of time variation within flow processing lines by initially identifying the various types of variation found in manufacturing environments. Here it is found that despite a wide variety of definitions of variability only two basic types exist, i.e. natural and special cause. From these definitions characteristics are identified from which a more precise method of defining individual types of variation has been developed. This method is presented with an example of its use in Chapter 3.

The measurement of variability is then examined in Chapter 3 with an examination of the various types of probability distribution used in its quantitative description. Overall the process of ensuring that the correct type of probability distribution is selected is found to be both time and resource consuming. Choosing a distribution type, therefore, is found to resolve into trade-offs between the degree of accuracy required from the results and the effort required to accurately determine both the probability distribution type and values for the measures that quantitatively define the distribution. Triangular distributions have, therefore, been selected for undertaking the experimentation work involved in this project because of their relative ease in undertaking such trade-offs. In this respect the various measures for quantitatively defining Triangular distributions were identified as measures of central tendency, levels of dispersion and the asymmetry of the dispersion of individual values about the measure of central tendency.

Chapter 3 then presents a detailed review of the past research undertaken to measure the effects of variability in flow lines. This work identified that no significant work has been undertaken to develop methods that can either:

- **a.** combine the individual elements of variability that arise within a workstation into a single variability probability distribution, or
- **b.** estimate the effects on individual workstation utilisation of differences in the levels of variability between workstations.

Upon examination, in Chapter 3, of the methods of dealing with variability in flow lines information derived from the above measurements is found to be essential to their successful deployment. Chapter 4 then describes the research undertaken to develop methods for determining values for these measurements with Chapter 5 detailing the results of this work. The research reported in Chapter 4 consisted of:

i. The extension of the method developed by Hopp and Spearman (1996) in combination with that used within PERT analysis (Ingalls et. al. 2004, Haga and Marold 2004) in the development and testing of a method for estimating the individual elements of variability that arise within a workstation into a single variability probability distribution measurement for a workstation.

ii. Extensive experimentation using computer simulation to develop methods of estimating the overall effect of variability on individual workstations.

Chapter 6 then discusses the work undertaken with Chapter 7 providing the main conclusions and Chapter 8 details of further work.

Chapter 2 Flow Processing Systems

2.1 Introduction

Black (1991) and Lei (2005) identify that for a company to successfully compete in today's competitive environment its manufacturing system must possess the capabilities to:

a. maintain high product reliability and quality whilst producing at a lower cost,
b. increase flexibility with respect to the variety and volume of products that can be produced,
c. provide quicker delivery of goods, and
d. improve delivery reliability.

Within high volume, low variety manufacturing industries achieving high levels of competitiveness has normally been achieved by the use of product-based 'flow' processing systems. Such lines are now becoming the preferred choice of manufacturing system for use within a wider range of industries due to their importance in providing an essential component of lean improvement practices (Katayama and Bennett 1996).

Flow based systems improve the flow of materials through manufacturing systems and hence reduce the lead time from entry of the raw materials to exit of the finished components. Implementing material flow by necessity requires the improvement of other areas significant to the performance of a manufacturing system such as reductions in work-in-progress levels, elimination of waste and the removal of non added value activities.

Within Chapter 2 the methods of designing flow processing systems are discussed and assessed in terms of the characteristics required to promote smooth flow of materials. From this analysis the limitations of such design methods are identified and suggestions made to resolve these limitations. The analysis performed identified that such techniques need to take into consideration, during the design process, the variability that exists within such lines. A detailed examination of the variability that exists within manufacturing systems then provides the subject for Chapter 3.

2.2 Characteristics of Flow Processing Lines

Hopp and Spearman (1996), Hayes and Wheelwright (1979) and Wild (1972) classify the various types of manufacturing environments as those listed in Table 2.1. In terms of their ability to process more than one product type there are primarily two types of facilities layout used, i.e. process orientated and product orientated. In the former structure identical and/or similar processes are located in the same area of the factory whilst in the latter processes are located on the shop floor according to the needs of specific products (Clarke et. al. 1993).

In general it is the level of product demand that determines the degree of investment possible and, therefore, which of these basic types of manufacturing system can be used (Hill 1985, Black 1991). High product demand can be used to justify the dedicated use of expensive, special-purpose machines whereas low demand requires the creation of a system capable of manufacturing a variety of products using inexpensive, multi-purpose items of processing equipment.

- ❑ High product variety/very low demand volume *job shop production,* where one-off items or small batch sizes are processed within a process orientated facilities layout.
- ❑ High product variety/low to medium demand volume *batch production,* where small to large batch sizes are processed within a process orientated facilities layout.
- ❑ Low product variety/medium to high demand volume *flow production,* where large batches of a single product or small number of product types are processed through a product orientated facilities layout.
- ❑ Low product variety/very high demand volume *continuous processing,* where a single product is processed through a continuous product orientated facilities layout.

Table 2.1: Basic Types of Manufacturing System

Those organisations that manufacture large varieties of components in low annual volumes within a batch manufacturing environment normally adopt process orientated. facilities layout also termed "functional" plant layouts, because of their inherent flexibility in changing product types quickly and economically. As stated, in a functional layout all operations of a similar nature are grouped together in the same department or shop floor area, which tends to encourage the processing of large batch sizes in order to reduce handling and set-up costs. Large processing batch sizes lead to higher work-in-progress costs, increases in queueing times and increased manufacturing lead-times. The problems common within such systems are well documented (Evans el al, 1990) and include difficulties in achieving short delivery lead times, maintaining reliable delivery dates, maintaining low manufacturing costs, and maintaining reliable quality.

In terms of high demand volume/low product variety environments the detailed characteristics of *flow production* have been identified by authors including Wild (1995) and Upton, (1994) and are listed in Table 2.2.

1. The operations required to process a product are allocated to individual work areas such that:
    a. the work areas can be laid out in a sequential manner in order to minimise backward movements of materials within the flow line,
    b. all products produced on the line have set routings, i.e. predetermined flows through sequentially dependent work centres,
    c. the line is balanced, i.e. the work content and labour allocation allocated to each work area, as near as possible, results in each work area having equal cycle times, and
    d. fixed cycle times are allocated to each work area that must be as near to, but not greater then, the TAKT time i.e. time required to meet customer demands.
2. Material flow through the line must be regular in that each work area must be able to pass its completed items to the next work area at the end of the TAKT cycle. There are a variety of methods by which this is achieved including mechanical pacing of the materials using conveyor belts.
3. The layout of work areas in relation to each other must attempt to minimise the distances moved by materials, provide sufficient space for in-process inventory, and provide visibility between work stations.
4. Product variety is normally low to minimise the amount of capital investment required in process technology and throughput rates are maximised to justify investment in process equipment.
5. A high level of process reliability is essential since a single machine breakdown can eventually bring a complete line to a halt. The planned maintenance of equipment during line operation can also result in line stoppages and hence may need to be undertaken out of production hours.
6. A high level of process capability is essential since the generation of defective items can interrupt materials flow through either the need to rework components or scrap components off the line.
7. The maximum amount of buffer stocks required between work areas must be predetermined such that sufficient physical space can be designed into the layout. Buffer stocks provide a 'decoupling' effect in that they enable greater flexibility in individual work area cycle times.
8. Inspection activities are difficult to incorporate within the line if they result in interruptions to materials flow.
9. Set-ups resulting from product type change-overs are both time consuming, interrupt materials flow and may even require line closure.
10. Operators normally perform a limited range of well defined and specialised work tasks.

Table 2.2: Characteristics of Flow Lines

There are a variety of flow production types in operation all of which have their manufacturing facilities arranged according to the needs of the product by arranging the operations in the same sequence necessary for manufacture of the product. The layout of process areas in this way usually takes the form of either:

a. a production line, in which machines are laid out in a straight line, as often seen in automotive manufacture, or
b. a manufacturing cell in which machines are contained within a specific area, e.g. cellular manufacturing and flexible manpower lines (Chan et. al. 2004).

The implementation of flow manufacturing has traditionally been through the use of *cellular manufacture* (Johnson et. al. 2004), which has been identified has bringing significant benefits when implemented in manufacturing environments containing high levels of product and process variety.

A cellular layout is said to lead to the best utilisation of operators' time and skills, of equipment utilisation and space and to increase flexibility in terms of the volume and variety of products that can be produced (Singh and Rajamani 1996). Initially developed by Flanders (1925) *cellular manufacturing* involves laying out processing equipment such that flow processing is possible for the production of a limited range of products or assemblies. Such systems attempt to incorporate the best practices and characteristics from traditional systems, i.e. general purpose processing equipment from job-shops, a facilities layout that promotes smooth materials flow from flow shops, small inventories from jobbing shops and small in-process inventories from continuous flow process systems (Clarke 1993).

In such systems the materials flow directly from one processing machine to the next with the minimum handling distance between movements. The cell area normally contains locations for raw materials, work-in-progress, machine tooling and other resources that promote the efficient operation of the machines. According to Upton (1995) these types of layouts attempt to minimise material handling requirements, encourage employee flexibility and involvement, provide conditions for multi-functional operators, promote good communications and visibility of products and promote simple visible patterns of material flow through the plant.

Where such lines produce mixed or multiple model types then batch processing may be employed. Here products are processed in batches through a limited number of operation routings. Sequential work areas are said to be disconnected when there is no automated pacing of material flows between them. Disconnected flow is achieved by allowing work-in-progress inventories to build-up between individual operations. This enables flow processing where variations in work content exist between sequential work areas (Kovalyov et. al. 2004).

Whether a flow line uses a non-mechanical or mechanical device, e.g. moving belt, to control the rate at which materials move through the line is no longer the overriding factor that determines its characteristics. Non-mechanical systems have been developed that share many of their characteristics with mechanically paced systems (Buxey 1979) i.e.:

a. items may need to be removed from a non-mechanical line in order to undergo processes that are shared with other lines or to be processed at sub-contractors facilities,

b. items may stay within the line and are effectively fixed to this line by the use of TAKT counters which determine the pace at which materials are indexed between work stations,

c. station overlap by operators may be possible,

d. no station overlap by operators may be possible due to limitations in operator flexibility,

e. more than one item may be made available to a work station either because the line is set-up to process batches or the product is sufficiently complex to require each work station to process a range of components, and

f. only one item may be made available to a work station in any one TAKT cycle to ensure minimum inventory levels exist.

2.3 Designing Flow Processing Systems

Gallagher and Knight (1986) identified that the design of cellular manufacturing involves identifying and grouping together families of components with similar processing operations or equipment requirements. Within these systems an individual flow production cell will then normally produce a product family. A commonly used method for categorising parts is *Group Technology* (GT) where a family of components can be identified using such techniques as classification and coding (Gallagher and Knight 1986) and production flow analysis (Burbidge 1975).

Lupton (1986), Parnaby (1979) and Hitomi (1979) considered that manufacturing systems can be treated as input-output systems in which inputs are transformed into outputs in the form of saleable products. Here, manufacturing system inputs include people, capital, materials, machines, information and a range of both internal and external social and economic factors.

Manufacturing systems have also been considered as a collection of sub-systems. These sub-systems form an integrated whole in which each sub-system possesses its own function and characteristics. This represents the 'systems approach' to the design of manufacturing systems where, according to Williams (1994), the complete system *"has more properties than the sum of the properties of its parts"*. Adopting this approach enables a complex manufacturing system to be designed by breaking it down into simpler sub-systems each of which are then individually designed.

Although this approach is said to enable individual system elements to be designed that satisfy a company's operational requirements (Hopp and Spearman 1991) individual system elements cannot be considered in isolation because of the inter-relationships that exist between them, i.e. a change in one element may have a significant effect on other elements and lead to reductions in overall system performance. An essential system element is that of the amount of work allocated to each work station since this is used to prevent disruptive interactions between system elements. Hence, a primary objective involved in designing flow processing systems is the effective allocation of individual work tasks to work stations, i.e. line balancing. The constraints that exist during the line balancing process are related to the allocation of each task to an appropriate work station (Carnahan et. al., 2001). If broken the constraints that result in non-feasible or inefficient flow line designs are:

a. precedence constraints, in terms of the order in which tasks need to be completed, should not be broken,

b. the line is balanced such that idle time throughout the line is minimised, and

c. total work task time allocated to a workstation should not be greater than the TAKT time.

In addition, feasible and/or efficient flow lines may also require one or more of the following:

a. either equal amounts of work to be allocated to each work station along the flow line or a specific work station or work stations to be allocated as much of the slack time as possible so that operators at these work stations can move between flow lines,

b. the sequencing and routing of the parts through the system to be set such that the number of change-overs required is minimised, and

c. technical constraints may require that work elements are placed on the shop floor near each other or placed at some distance apart.

These constraints assume that variability in terms of operator task times and the occurrence of change-overs and equipment breakdowns will either have little effect on line efficiency or need only be considered at the subsequent operations planning stage and not at the flow line design stage.

Determining the allocation of work tasks to work stations within mixed-model and multi-model lines is more complex and additional decisions that need to be made include determining:

a. the batch sizes of each model, and
b. the sequence in which models are launched onto the line, i.e. this is concerned with both the ordering of models onto the line and the time interval between launching models onto the line.

Arden-Finch, (2000) also pointed out that *"usually, the time and resources available for designing a 'balanced' flow line are limited and, hence, they are often designed without knowledge of the exact times required for such activities as quality checks"*. Once the cell is operational attempts are then often made to reduce activity times through improvement activities (Imai 1986) and hence significant redesign of the flow line may then result from these improvements.

Approaches to the line balancing problem proposed include mathematical models (Hillier et. al. 1967), heuristics, optimisation techniques and simulation modelling. Mathematical algorithms used include Salveson (1955) and Bowman (1963) who used linear programming. However, this latter technique is impractical for designing complex flow lines which contain large numbers of workstations.

Heuristics methods developed to overcome these size limitations include those developed by Kilbridge and Wester (1961), Arcus (1966) and the Ranked Positional Weight technique (RPW) developed by Helgerson and Birnie (1961). All such methods are approximate methods which cannot guarantee optimal solutions being found (Wild 1985). Using the RPW method, tasks are prioritised according to position in the product processing sequence, i.e. tasks are assigned to workstations based on their ranked positional weight value with highest RPW values tasks being assigned to work stations first.

Arcus (1966) developed a computer based heuristic method, Computer Method of Sequencing Operations for Assembly Lines (COMSOAL) that generates random sequences. By generating these random sequences, the method may move around the set of possible sequences and is, therefore, likely to find a good solution.

Design methods for the operator walk cycles of flexible manpower lines are manually based and require both past design experience and several design iterations to generate acceptable cycles. This is confirmed by Black (1991) who provides detailed descriptions of this type of system. The use of such manual techniques limits the complexity of systems that can be designed and hence restricts their usage.

The use of simulation techniques includes the use of queueing networks, (Solberg 1976, Suri and Diehl 1985, Whitt 1983). Solberg (1976) developed CAN-Q (Computer Analysis of Networks of Queues) to model and analyse queueing networks, that assumes that service and transport times are exponentially distributed and that the service discipline is First In First Out (FIFO). Solot and Bastos (1988) further developed a queueing network to allow multiple pallet types to be modelled. Suri and Hildebrant (1984) developed MVA-Q, an extension of CAN-Q that enabled a variety of part types to be modelled. It can be seen from this work that the use of queueing models is inflexible since unique queueing equations need to be developed for each individual flow line design problem.

Methods involving discrete event simulation, using software packages such as Witness (1991), ProModel (1993), Simfactory (1990), GoldSim (1990), Arena (2002), Modsim (2001), EM-plant/Simple++ (2004), Taylor II (2002 -2003), Taylor ED (2001), and Modular Manufacturing Simulation (1996) overcome the limitations of queueing theory. Simulation is now often seen as the only effective means of evaluating the complex dynamic interactions that occur between manufacturing system elements. Although realistic models can be developed, the creation of a simulation model is often difficult and time-consuming. Successful use of simulation also depends on the user expertise to correctly interpreting the results of a simulation run to make system design improvements. Intelligent simulation systems have been proposed that overcome this need for user expertise, i.e.:

a. Shannon et. al. (1985) linked expert systems with simulation for solving manufacturing problems,

b. Wang and Bell (1991) developed a knowledge-based modelling system for designing flexible manufacturing systems, and

c. Stockton and Finch (2000) developed automatic systems for designing flexible manpower lines by linking a commercial simulation system with genetic algorithm based optimisation routines.

Traditional flow processing systems are unable to efficiently operate with large amounts of product, process or demand variability. Such systems are designed to cope efficiently only within the conditions for which they were initially designed, i.e. typically they would be designed for:

a. stable demand,
b. high and limited range in production volumes,
c. limited variability in product mix ratios,
d. limited range of processes,
e. limited range of tooling,
f. limited process route options,
g. continuous production, and
h. single products or a limited range of products that were similar in design.

The underlying design philosophy is to minimise the variety that needs to be dealt with. For example, using GT during the development of cellular manufacturing systems, the variety of components manufactured by a company are grouped into families. Manufacturing cells are then designed for processing individual families in which component variety has been much reduced, i.e. components within a family are similar in terms of such characteristics as part shapes and sizes, part dimensional tolerances, operation and/or processing equipment requirements.

Limitations to product, process and demand variability are, therefore, built into the system from the initial design. If the requirements of the cell change due to variations in product mix, variations in volume or introduction of new products, the effects on the operation of the cell can result in poor utilisation of processing resources, over utilisation of other resources and the inefficient use of manning, (Sethi et. al. 1990).

2.4 Requirements for Effective Materials Flow

The term 'flow' is normally used within manufacturing to represent the movement of materials through the sequence of processes required to convert raw materials to finished components. The time taken for a production job to flow from one work area to the next within a manufacturing environment is normally composed of some or all of the individual task times listed in Table 2.3. Both Jonsson and Lesshammar (1999) and Azzone et. al. (1991) support the use of 'time' to measure the flow orientation of a system although Jonsson and Lesshammar (1999) suggests that its use must form part of an integrated set of performance metrics which would need to include inventory levels, turnovers, throughput times and service levels. It can be seen that the tasks listed in Table 2.3 are related to many of these additional performance metrics.

Hopp and Spearman (1996) point out that because such a sequence of processes is a 'network of interacting parts' managing these interactions is as important as managing both the individual processes within the sequence and the materials as they move between them.

a. work area waiting, i.e. the time a work area waits for its next job to be finished on the preceding work area, b. set-up, i.e. the time taken to adjust or change tooling or equipment prior to processing the production job, c. processing, i.e. the time taken performing a manufacturing process on the production job, d. stoppages, the time processing is halted whilst problems, such as breakdowns, lack of materials, are resolved, e. job waiting or queueing, i.e. the time a production job waits after finishing a process before the next process is ready to receive it, and f. move to next facility, i.e. the time taken in handling a production job between workstations.

Table 2.3: Types of Task Times within Manufacturing

Within a batch production environment set-up, process and queueing times play a significant role in determining the efficiency of the system. In a flow processing system the interaction between work areas also plays a significant role. A fundamental requirement in order to create efficient flow of materials through a flow line is, therefore, synchronisation of the work task times between work stations.

Comparing the basic types of manufacturing systems listed in Table 2.1 it is the level of synchronisation in terms of the degree of interruption in the movement of materials flow between sequential processes (Clarke 1993) that provides significant differentiation between them. Here, the literature is agreed on which of these systems represent the extremes in material flow, i.e.:

a. at one extreme the materials may move through each processing stage within a manufacturing system incurring long waiting periods between each stage, i.e. job shop and batch production, and

b. at the other extreme the products move from one process stage to the next without any interruptions in this movement, i.e. continuous processing.

The variety of activities that can effect the synchronisation of task times along a flow line can be categorised according to whether they:

a. always occur within each TAKT cycle,
b. may possibly occur within some TAKT cycles,
c. always occur between TAKT cycles, and
d. may possibly occur between some TAKT cycles.

In order to achieve efficient material flow along a flow line, work areas:

a. must be available to begin their allocated work at the start of the TAKT cycle , and
b. must complete their work by the end of the current TAKT cycle, i.e. to ensure that they can pass materials onto the next work station and receive materials from the previous work station ready for the start of the next TAKT cycle.

Hence, whether these activities occur within or between TAKT cycles is less relevant than their effect in delaying the end of a TAKT cycle and, therefore, delaying the start of the next TAKT cycle.

2.5 Causes of Time Variation within Flow Lines

The work of Ford (1926), Charney (1991) and Hopp and Spearman (2000) indicate that variation is an effect resulting from one or more underlying causes. Researchers including Blumenfeld (1990), Wild (1973) and Conway and Maxwell (1987) have identified a wide range of individual sources of variability including variability in equipment functioning and process operating capabilities, set-up times and reliability, operator absenteeism, operator abilities, motivation and skill levels, material and product quality, cycle times, delivery reliability of raw materials and components, and batch sizes both procured and produced.

The current research is concerned with the causes of time variation that affect the individual 'time-consuming' activities occurring within manufacturing environments. These basic 'time-consuming' activities are well known and have formed an essential element of the Work Study (Wild 1985) methodology, i.e.:

a. **processing activities** that transform raw materials to finished products,
b. **inspection activities** that determine if products or components meet customer specification requirements,
c. **handling activities** that involve moving materials from one location to another, and
d. **storage activities** which are either unplanned delays or planned delays in the processing cycles of components where materials are waiting for the next operation to take place.

Using these basic Work Study categories the work of Wild (1973) and Hopp and Spearman, (1999) can be used to categorise the main activities taking place within a manufacturing environment as those listed in Table 2.4

Activity Category	Activity
Processing & Inspection	Processing part, e.g. turning, heat treating, forging Inspecting part
Handling	Loading part onto processing equipment Unloading part from processing equipment Transport between process operations
Waiting	Waiting repair of processing equipment Waiting completion of planned maintenance Waiting set-up and change-over operations Waiting tool changing Waiting in in-process inventory for next process Waiting completion of batch Waiting inspection Waiting for jobs Waiting for materials

Table 2.4: Basic Activities within a Manufacturing Environment

Each of the operation types shown in Table 2.4 requires generic resources for their performance. Again identification and classification of these generic resources has been the subject of Work Study research, i.e.:

a. **Materials** which represent raw materials and purchased components input into the manufacturing system, in-process inventory that arises between processes, and finished goods,

b. **Equipment** which represents the items of processing equipment used to convert raw materials to finished goods,

c. **People** who are the personnel, such as operators that, perform the processing activities, and

d. **Methods** which represent the operating procedures by which processing activities are undertaken.

Nadler (1970) also identified the basic characteristics of a manufacturing system as:

a. **Function** – the function or purpose of the system,

b. **Inputs** – the resources (material, information, money) input into the system to achieve the function,

c. **Outputs** – the output products required to achieve the function,

d. **Physical Catalysts** – the methods and equipment used to change inputs to outputs,

e. **Sequence** – the individual stages involved in converting inputs to outputs,

f. **Human Agents** – the personnel responsible for the collection of inputs and their conversion to outputs, and

g. **Environment** - the higher level system that the system forms part of.

It can be seen that of these 7 characteristics b, c, d, e and f represent generic manufacturing resources, i.e. materials as *inputs and outputs*, equipment as *physical catalysts*, methods as *sequences* and people as *human agents*. Hopp and Spearman, (1996), identify the main sources of variation as people, materials, methods, equipment and environment. In addition, Information must also be considered as an essential resource and hence a source of variation since manufacturing systems efficiency is becoming increasingly dependent on outputs from information systems such as ERP and MRP. Nadler's work (1970) indicates that a comprehensive list of sources of variation would need to include Function and Environment. However, for the purposes of the current research these will not be included since it will be assumed that variations in both the Function and Environment of a manufacturing system would be expected to result in changes to internal activities and resources. The following is a brief list of the sources of variability that may occur within these system characteristics:

(a) set-ups,

(b) batch sizes,

(c) job allocations,

(d) tool changes,

(e) layout designs,

(f) absenteeism levels,

(g) skill levels,

(h) levels of operator knowledge,

(i) rework levels,

(j) material defects, and

(k) product launch intervals.

Chapter 3 Variation within Flow Processing Systems

3.1 Introduction

The need to deal effectively with variability is important since some forms of variability provide improved competitiveness, (e.g. product variety, technological change and demand variability), whilst others are detrimental to competitiveness, (e.g. set-ups, machine failures, yield loss and rework, skill differences and engineering changes). In terms of flow processing lines, provision of wider ranges of products must be achieved whilst maintaining or reducing costs, lead time and delivery reliability.

Goldratt (1984), Hopp and Spearman (1996) and Davis (2000) have interpreted variation as a natural phenomenon with Hopp and Spearman, (1996) making the assumption that "*it is everywhere and because of this, it can be quite difficult to define precisely what might be the cause of any particular example of variability*". This assertion is of course correct in the context of variation to some extent being evident in all activities that occur within manufacturing environments and the features of their physical resources. This chapter will provide methods of classifying the various types of variation found in manufacturing environments.

This chapter also examines the subject of time variation within manufacturing environments and begins by identifying and analysing the various causes of such variation. Chapter 2 identified that these are primarily associated with the wide range of processing, inspection, handling and storage activities that take place within the manufacturing environment. The time taken to perform each type of activity may be subject to a range of variability sources that have either a direct or indirect effect on the variability of their activity times.

In addition, the methods of quantitatively measuring variation will be identified. Here, there is a need to provide two measures for each variability source, i.e. the event time when the cause of variability starts and the length of time the cause exists.

3.2 Types of Variation

Within the quality control research domain a wide body of literature is available from which basic types of variability can be identified. For example within the work of Lakhe and Mohanty (1994) and Hopp and Spearman (1996) the types of variation examined include Assignable, Special Cause, Controllable, Natural, Random, Inherent and Common Cause.

In the non-quality research literature Ljungberg (1998), Nord et. al. (1997) and Tajiri and Gotoh (1992) have classified the disturbances that occur within manufacturing in terms of 'chronic' and 'sporadic' depending on how often they occur. Definitions provided by Jonsson and Lesshammar (1999) for these are:

"Chronic disturbances are usually small, hidden and complicated because they are the result of several concurrent causes".

"Sporadic disturbances are more obvious since they occur quickly and as large deviations from the normal state. Such disturbances occur irregularly and their dramatic effects are often considered to lead to serious problems".

Hopp and Spearman, (1996) categorise types of variability within manufacturing environments in terms of when they occur as follows:

a. natural variability, i.e. the variability occurring continuously that is inherent in the natural process such as variations in the rate at which manual work is performed,

b. pre-emptive outages which force stoppages of processing whether or not the current work cycle is completed, i.e. unscheduled downtimes caused by such events as machine breakdowns, and

c. non pre-emptive outages, i.e. scheduled downtimes or stoppages of work cycles, for such activities as planned maintenance, tool changing and component change-overs.

The assertion of Hopp and Spearman, (1996) that only two types of variation exist, i.e. random and controllable, is true since:

a. Assignable, Special Cause, and Controllable possess the same basic characteristics and are, therefore the same type of variation, and

b. Natural, Random, Inherent, and Common Cause possess the same characteristics and are, therefore the same type of variation.

A range of definitions appear in the literature for these two basic types of variation including:

3.2.1 *Assignable, Special Cause, and Controllable*

Definitions used by Horel et. al. (2002), Montgomery (2001), Britz el. al. (2000) include:

a. precise timings when events occur are unknown and unpredictable and therefore are beyond the immediate control of management, e.g. machine breakdowns and power failures,
b. events occur as a direct result of planning and control decisions and hence their timings coincide with the implementation times of these decisions, e.g. a shift change may result in the use of an inexperienced operator causing quality defects or reducing the work pace of an operation,
c. events that are easily and readily identified and can be corrected by local action e.g. change of operator during a production period, variation in material quality from supplier to supplier,
d. differences in output that are abnormal and cannot be predicted,
e. causes are extraneous to the process and disrupt or interfere with the routine operation and normal dynamics of the process, and
f. large sources of variation that can potentially be traced to their cause.

3.2.2 *Natural, Random, Inherent, and Common Cause*

Definitions used by Horel et. al. (2002), Montgomery (2001), Britz el. al. (2000) include:

a. occurs in a natural process time with no planned or unplanned outages even if related to operators, consequences of events beyond our immediate control, e.g. the process time of any workstation in the flow line, and

b. small, random force that acts continuously on a process, when a process varies in such a way that, over time, it becomes predictable.

From these definitions characteristics can be identified from which to define in a more precise manner individual types of variation, i.e.:

i. Level of variation caused by an event.

ii. Time when the event occurs that causes the variation.

iii. The predictability of the timing of the event that causes the variation.

iv. Whether the cause of the timing of the event is known.

v. Whether methods are available for controlling the timing at which the event occurs.

vi. Whether the length of time over which the event causing the variation occurs is predictable.

vii. Whether the cause of this time length for the event is known.

viii. Whether methods are known for controlling the time period over which the event occurs.

ix. Whether the level of the variation resulting from the event is predictable.

x. Whether the cause of this amount of variation resulting from the event is known.

xi. Whether there are methods available for controlling the level of variation resulting from the event occurring.

An example of the use of these characteristics in defining an individual source of variation is provided in Table 3.1.

	Predictable	**Knowledge of Cause**	**Knowledge of Controlling Method**
Time when event occurs that causes variation	YES – begins to occur at the start of an operator's shift	YES - operator assigned to tasks for which no training has been received	NO – unknown how jobs are allocated to operators
Length of time over which event causing variation exists	YES – occurs randomly over a complete shift period	YES – length of time is that of a single shift period	NO – not possible to remove shift or transfer jobs between shifts
Level of variation caused by the event	NO – no study yet undertaken to assess extent of variation	YES – lack of operator training	NO – at moment no training programme exists for the tasks in question

Table 3.1: Defining Work Pace Variability resulting from an Untrained Operator

3.3 Types of Probability Distributions

Variation by its stochastic nature is primarily quantified using probability distributions. A wide variety of distribution types have been found to exist in manufacturing (Moodie and Young 1965, Kao 1976, 1979, Nkasu and Leung 1995) including Average, Fixed, Erlang, Gamma, Weibull, Poisson, Coxian distributions and those illustrated in Figure 3.2.

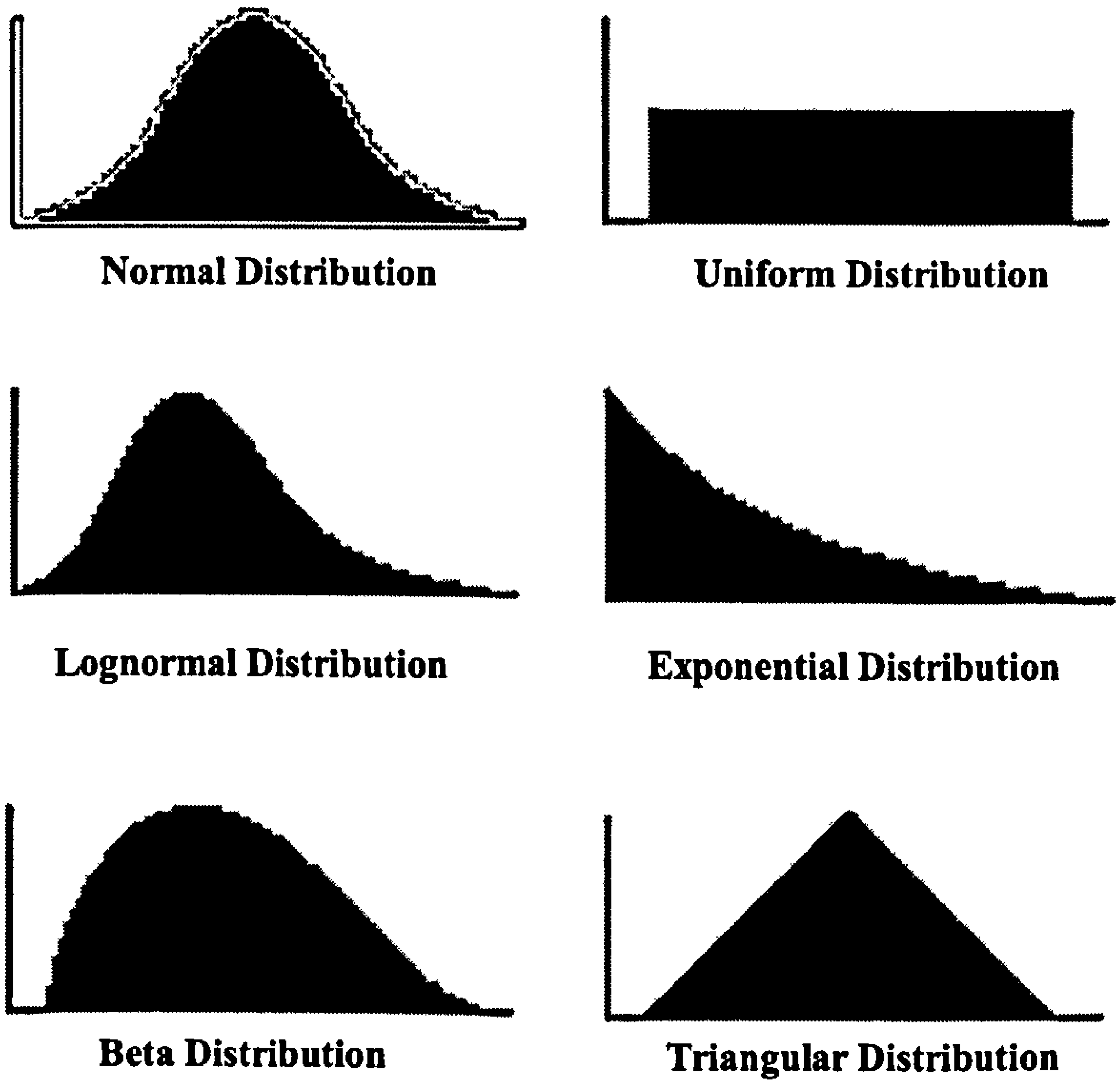

Figure 3.1: Types of Probability Distributions in Manufacturing [Ebeling, 1997]

Identifying the precise distribution type that applies to any particular manufacturing situation requires the collection of real data and the analysis of this data in terms of the distribution type. For example the stochastic nature of workstation task time variation from cycle to cycle primarily arises from the use of human operators (Buzacott 1990, Scholl 1999). Identifying the distribution type in this instance would require a large number of random observations of individual operator's task times. Consideration would need to be given to ensuring that bias was not introduced in terms of the timing of observations during the working period, the skill and motivational levels of the operators being observed and the variation in the materials and work methods used. Overall this process would be both time and resource consuming. Choosing a distribution type, therefore, can resolve into trade-offs between the degree of accuracy required from the results and the effort required to accurately determine both the probability distribution type and values for the measures that quantitatively define the distribution, e.g. the mean and standard deviation of the normal distribution. In this respect when designing flow processing lines such data is often not available. Hence, it is often more appropriate to select distributions such as the Uniform, Average or Triangular distributions.

Of these distribution types the Triangular distribution provides an acceptable trade-off between accuracy of results and ease of estimation of the distribution parameters. In this respect the Triangular distribution function can be completely defined by estimating, for an activity, its absolute minimum time value, most likely time value, and absolute maximum time value. Both the absolute minimum and maximum values can be skewed about the most likely value to provide a skewed distribution if appropriate. Triangular distributions are primarily used within project management, (Ingalls et. al. 2004, Haga and Marold 2004), where they form the distribution type employed in the Programme Evaluation Review Technique (PERT).

3.4 Measures of Probability Distributions

Three basic characteristics of a probability distribution are normally used in its quantitative definition, (Chou 1970) i.e.:

i. A measure of its central tendency, i.e. that single value about which the individual items in a series tend to be distributed and concentrated.

ii. A measure of the level of variation of its individual values, i.e. their dispersion about the central value.

iii. A measure of how individual values are skewed about the measure of central tendency, i.e. the asymmetry of the dispersion of individual values about the measure of central tendency.

3.4.1 *Measures of Central Tendency*

Table 3.2 provides definitions of the alternative methods of measuring the central tendency of a probability distribution.

a. **Arithmetic mean** is the sum of the observed values in a sample divided by the number of observations in the sample, b. **Geometric mean** is the n^{th} root of the product of n observed values, c. **Harmonic mean** is the reciprocal of the arithmetic mean of the 'reciprocals of the observed values', d. **Median** is the value of the middle observed value in a series that are arranged according to manitude, i.e its position in a series is such that it divides the series into two equal parts, e. **Mode** is the value in a series of observed values which appears more frquently than all other values.

Table 3.2: Measures of Central Tendency

3.4.2 *Measures of Dispersion*

Here there are two basic states to consider, i.e.:

i. **Distributions that share the same mean.** Here Table 3.3 provides definitions of the alternative methods of measuring the dispersion of distributions that share the same mean.

a. **Range** is the difference between the highest and lowest values in a series of observed values, b. **Variance** is the mean of the squared deviations from the mean, and c. **Standard deviation** is the square root of the variance.

Table 3.3: Measures of Dispersion of distributions that Share the same Mean

ii. **Distributions that have different means.** Here the primary method of measuring the dispersion of distributions that have different means is the Coefficient of Variation (CV) which is defined as the ratio of the standard deviation to the mean. This measure is useful since absolute measures of variability such as the variance do not reflect the relative amount of variability in relation to the mean of the value that is varying, e.g. a variance of 100 μm would represent low variability in the length of a shaft with nominal length of 50 mm, but would represent high variability for line widths on a microchip whose mean length is 5μm.

Hopp and Spearman (1996) use relative degrees of CV to classify levels of variability as follows:

a. low variability, for example are process times without stoppages, when CV is < 0.75,

b. moderate variability, for example are process times with short set-ups, when CV is ≥ 0.75 < 1.33, and

c. high variability, for example are process times with long breakdowns, when CV ≥ 1.33.

3.4.3 *Measures of the Skewness*

Here the primary method is that of the **Pearsonian coefficient of skewness** which is defined as the ratio to the standard deviation of the difference between the arithmetic mean and the mode.

3.5 Measuring the Effects of Variability in Flow Lines

An early attempt at measuring the effects of variation within flow lines was that of Hunt (1956) who developed queueing models for a two-workstation flow line capable of determining the maximum possible utilisation of the line and the mean number of units in the system. The models were developed using exponentially distributed service times with a coefficient of variation of 1.0 and Poisson distributed arrival times. The work assumed that no variation existed in terms of movement between workstations, i.e. that units were transferred instantaneously between stages, and that service commenced instantaneous upon arrival at an empty stage, i.e. no variation in terms of set-ups. The models were used to undertake experiments using infinite storage space between stages, no storage between stages, and finite storage space between stages. The experiments identified that where blocking is experienced the maximum possible utilisation decreased as the number of workstations increased and that utilisation increased exponentially with small increases in buffer sizes.

Attempts to derive models applicable to production lines with greater numbers of workstations by Freeman (1968, 1969) focused on deriving empirical models for determining the utilisation of such lines. This work used the output data from simulation experiments to developing regression based models.

Anderson and Moodie (1969) used outputs from a simulation model to estimate the coefficients for an optimal solution to the problem of determining the buffer storage capacity for lines of varying lengths, i.e. ranging from 2 to 5 workstations. The objective of the work was to develop models to determine the optimum buffer size for workstations. Normal distributions were used to represent the workstation cycle times with a coefficient of variation of 0.3, i.e. as with the earlier work of Hunt (1956) only a limited amount of variability was considered.

Using theoretical and intuitive reasoning Knott (1970) developed a model that contained a factor the value of which depended on the specific features of a flow processing line.

Again as with earlier work this model could not be generally applied without further effort in identifying appropriate values for this factor. This work reviewed the inefficiency of a series of workstations with allocated buffers and developed formulae to balance workstations using a computer simulation package. His results compared well with those of Hillier and Boling (1967) and Freeman (1968).

Payne, Slack and Wild (1972) undertook experiments using computer simulation models in order to investigate the idle time and maximum queues occurring at stations on flow lines with "balanced" independently normally distributed station service times. The experiments were restricted in terms of the levels of variability examined, i.e. all experiments had workstation mean times of 10 time units and the coefficient of variation of the experiments ranged from 0.1 to 0.3. Wild and Slack (1973) later used computer simulation experiments to identify the effects of line length, cycle time variability and inter-station buffer capacity on output efficiency and workstation idle time. The means and coefficients of variation of the workstation time distributions remained the same as in earlier work (Payne, Slack and Wild 1972) but adopted buffers with maximum capacities. Their results indicated that idle time at any workstation was dependent on the position of the workstation in the flow line, i.e. with idle time increasing along the line. Idle time at any workstation was also found to be dependent on the inter-station buffer capacity of the line with idle time decreasing as buffer capacity increased.

Carnall and Wild (1985) carried out simulation experiments to determine the effect on output efficiency and average idle time of buffer capacity, service time variability, and the order of placement of constant work time and variable work time stations along the flow line. Positively skewed work time distributions with coefficient of variations of 0.1 to 0.5 where used to build models of up to 10 workstations employing buffer capacities of 1 to 3 units. Their results supported the hypothesis that the order of constant and variable stations on an integrated, unpaced, notionally balanced line had an effect on line performance, i.e. grouping variable work time stations at the end of a flow line rather then in the middle provided improved yields of up to 3%. This effect, confirmed the existence of a 'bowl' shaped phenomena similar to that reported by Makino (1964) and Hillier and Boling (1966). Carnall and Wild (1985) recognised the practical limitations in the use of the results of their work due to technological, precedence and zoning constraints limiting the freedom of workstation placement.

El Rayah (1979) carried out computer simulation experimentation to determine whether deliberate unbalancing of flow lines improved the output rate of a line. Three basic configurations of workstation operation times, using 3, 4 and 12 workstation flow lines, were explored, i.e. short times-long times-short times, long times-short times-long times and short times-medium times-long times. Simulation models made use of normally distributed workstation times all with equal coefficients of variation, i.e. 0.15, and buffer sizes of 2 to 4 work items. Only the 'long times-short times-long times' configuration was found to result in improved output rates when compared with perfectly balanced flow lines. The work of El Rayah (1979) again confirmed the existence of the bowl phenomena initially identified by Makino (1964) and Hillier and Boling (1966). The practical application of the bowl phenomenon appears to provide a method of increasing the throughput of flow processing lines with variable processing by purposely unbalancing the line in a certain manner (Hillier and Boling 1979). In this respect Hillier and So (1993) have shown that the 'bowl' phenomenon can be applied to the optimal allocation of work for somewhat larger flow processing lines than previously considered by Hillier and Boling (1966).

Rao (1975 a, b) considered the unbalancing of flow lines with exponential-Erlang and exponential-normal arrival and service times. They concluded that as a guideline for both these systems that *"improvement in the production rate occurs by unbalancing the system in such a way that the less variable stage is loaded slightly more than the more variable stage"*. Mishra et. al. (1985) extended this research to a service time distribution common in maintenance functions, i.e. the hyperexponential distribution and found that the guideline, formally identified, was violated in such systems.

A model for determining throughput, although providing only estimates, was developed by Muth (1987) for general values of mean processing time, coefficient of variation of these processing times and number of workstations within the production line. This model was based on earlier work (Muth 1977, Alkaff and Muth 1987) that used a combination of theoretical analyses and numerical curve-fitting in its construction. This model provided accurate estimates of throughput, i.e. less then 5% errors, when tested using several data sets, i.e. Hillier and Boling (1967), Freeman (1968) and Silver (1978). However, this model was restricted to production lines with zero buffer quantities between workstations.

In order to overcome zero buffer size restrictions Blumenfeld (1990) developed an extension of Muth's (1987) model. To include buffer size as a variable the model developed by Hunt (1956) was used to provide the analytical form of this extension. Close agreement was found when compared with results from studies by Hillier and Boling (1967), Freeman (1968) and Knott (1970).

Slack and Wild (1980) examined the operational characteristics of a flow line under non-steady-state conditions in which equipment breakdowns occurred. Results indicated that the transient increase in workstation idle time was approximately linearly related to increasing line length. Their results implied that the total transient idle time could be minimised if the workstations incurring equipment breakdowns were placed in the middle of the flow line. The deliberate unbalancing of the flow line in this manner was viewed, by the researchers, as an alternative to isolating workstation equipment breakdowns by the use of the buffers.

Conway et al (1987) explored the effect on throughput levels of the distribution and quantity of buffer inventory within flow lines that either possess variability of processing times that differ between workstations, or are unbalanced and/or contain unreliable workstations. Computer simulation models of flow lines were used to identify both optimum positions for buffers and their optimum quantities. Workstations were examined with uniform distributions for workstation times and exponential time distributions for machine breakdowns, and coefficient of variations ranging from 0.1 to 1.0. Their experiments in terms of unbalanced flow lines assumed that within the line a bottleneck workstation exists that would restrict the throughput rate. From their results they observed that "*with a severe bottleneck the adjacent stations are almost always finished before the bottleneck. This prevents blocking and starving of the flow-limiting station, so line throughput is near the maximum attainable.*" In these circumstances, they argue that adjacent stations serve as buffers for the bottleneck. Material flow was controlled within their models using a push mode with unlimited availability for raw material and unlimited demand for finished products. In addition it was assumed that material always moved forward as soon as a workstation is available.

More recently Taylor and Heragu (1999) have simulated flow lines with a range of buffering strategies and cycle times that possessed a variety of means and variances. Work-in-progress and cycle time improvement resulted from reductions in the mean and variance of workstation job times. The level of improvement varied greatly depending on the type of distribution being investigated.

Khalil and Stockton (2003) used Taguchi orthogonal arrays to design a series of experiments from which the effects of individual flow line characteristics on overall line throughput could be identified. Results indicated that short frequent stoppages, such as equipment set-ups, have a greater effect on line efficiency than long infrequent stoppages, such as machine breakdowns. In addition, the frequency of stoppages tended to have a greater effect then the length of stoppages.

The approach of Hopp and Spearman (1996, 2000) to determining the effects of variability initially required the estimation, using Equation 1, of workstation 'availability', i.e. the proportion of time the workstation is available to process components.

$$A = m_f \, . \, (m_f + m_r)^{-1} \tag{1}$$

Where:

A = Workstation availability resulting from the occurrence of stoppages caused by such activities as changeovers, equipment breakdowns and planned maintenance.
m_f = Mean time between occurrence of stoppages, i.e. number per time period.
m_r = Mean stoppage time.

Equation 1 makes use of the reliability measurements (Kapur and Lamberson 1977) used within maintenance planning, i.e.: the Mean Time to Repair (m_r) and the Mean Time to Failure (m_f).

Using the measure of workstation availability arising from Equation 1 the workstation cycle time is modified to provide an 'effective cycle time' using Equation 2.

$$t_e = t_o \,.\, A^{-1} \qquad (2)$$

Where:

t_e = Effective cycle time.
t_o = Workstation cycle time.

3.6 Dealing with Variability

A number of strategies have emerged for dealing with the effects of variability within manufacturing operations, i.e.:

a. through the effective allocation of tasks to workstations during the line balancing procedure,

b. effective sequencing of work items onto the flow line,

c. adoption of an optimum mechanism for controlling material flows,

d. removing the causes of variation, e.g. through set-up reduction and total quality management activities,

e. reducing the levels of variation from individual causes, e.g. through lean-based waste reduction techniques,

f. combining sources of variation, i.e. through variability pooling and buffering, and

g. use of flexible resources to off-set the effects of variability.

3.6.1 *Line Balancing, Sequencing and Material Flow Control*

Assembly line balancing techniques for single product flow lines normally assume that task times are deterministic. A number of strategies have been developed to cope with situations in which stochastic task times exist. These primarily involve transforming the stochastic problem into a deterministic problem by the use of a TAKT time that possesses a limited probability of being exceeded in practice by a single workstation task time (Kottas and Lau 1973, 1981, Sphicas and Silverman 1976, Henig 1986, Carraway 1989). Where such solutions have been employed it is normal to make provision for isolated cases in which a task time does exceed the TAKT time by:

a. stopping the line until incomplete operations have been performed,

b. providing off-line stations to complete such items, and

c. use of mobile workers and/or use of additional workers.

The incompletion costs arising from these strategies have been examined by Kottas and Lau (1973) who identified that the higher the potential incompletion costs of a task then the more idle time that must be introduced into a station in order to avoid actual incompletion.

Other strategies developed include the use of a sensitivity analysis to establish the stability of a solution derived from a line balancing exercise ((Sotskov et. al. 2003), use of Simulated Annealing (Suresh and Sahu 1994), a genetic algorithm (Suresh et. al. 1996) and an 'ant' algorithm (McMullen and Tarasewich 2003). An additional strategy, that seems to be largely ignored in practice, is the deliberate unbalancing of work allocations to workstations such that advantage can be taken of the 'bowl' phenomenon identified by Hillier and Boling, (1966).

Mixed-model and multi-model assembly lines allow more than one model type or model variation to be produced on the same flow line. The normal approach is to use 'average' times to balance the allocation of work tasks to workstations. According to Becker and Scholl (2003) *"finding a line balance whose station loads have the same station time and equipment requirements whatever the model produced is almost impossible"*. Additional decisions that can help to improve workstation utilization include determining the batch sizes of each of the models and the sequence in which the models are launched onto the line (Yano and Bolat 1989, Bard et. al. 1992, Scholl 1999), i.e. this later decision is concerned with both the ordering of models onto the line and the time interval between launching models onto the line. The objective of mixed-model sequencing is to determine the order in which product types should be produced such that:

a. production of each product type is evenly spread throughout the day,
b. a set sequence can be identified that allows materials to flow smoothly down the production line, i.e. this sequence is normally repeated until demand levels change,
c. each product's daily requirements are produced each day,
d. the workload is distributed evenly at each workstation, and
e. excessive problems with change-overs are not experienced.

If any appreciable variation in demand or product mix occurs then the efficiency with which line sequencing can be performed quickly falls.

In terms of the use of appropriate material flow control mechanisms Kim et. al. (2003) compared the performance of three alternatives, i.e. output flow control (OFC), bottleneck flow control (BFC) and dynamic flow control (DFC). Where low levels of variability existing the use of BFC provided higher output levels with OFC providing slightly lower levels of work-in-progress and improved delivery reliability. In terms of medium levels of variability BFC outperformed all other methods in all performance measures. However, where high variability existed the BFC yielded higher output levels, OFC and BFC were similar in terms of reducing work-in-progress levels and BFC improved delivery reliability.

3.6.2 *Variability Removal and Reduction*

A number of methodologies have evolved that seek, in part, to reduce sources and levels of variability, i.e.:

i. **Total quality management** (TQM) is a process that seeks to continuously reduce the level of quality defects generated and, therefore, eliminate or reduce sources of process time variability (Varghese 2004).

ii. **Total productive maintenance** (TPM) seeks to improve the process capability, processing reliability and output performance of production equipment using planned maintenance practices. The effect of long breakdowns on flow lines can be in part be resolved using planned maintenance outside the normal line operating work period (Nakajima 1988).

iii. **Set-up reduction,** (Hay 1989, Mileham and Culley 1994), seeks to minimise the time and standardise the procedures required in changing-over from one component type to another. According to Hall, (1983) and Steudel and Desruelle, (1992) rapid changeover is fundamental to implementing effective flow processing systems.

iv. **Continuous improvement** seeks to identify and remove sources of waste within a manufacturing environment and hence leads to reductions in levels of variability arising from these sources.

v. **5S exercises** seek to provide working conditions designed to promote standard methods of work hence reducing variability arising from work method differences.

vi. **Standard operating procedures** provide standard methods by which work is undertaken and hence remove variability caused by the use of different methods.

3.6.3 Variability Pooling and Buffering

Variability pooling involves combining multiple sources of variability. Such pooling tends to reduce the overall effect of variability by making it less likely that a single occurrence of high variability will have a significant effect on overall performance. Variability pooling can be achieved in the following ways:

a. **batch processing,** i.e. the process times of batches are less variable then the process times of individual parts provided that all process times are independent and identically distributed,
b. **queue sharing,** i.e. the use of a single queue of jobs awaiting processing at one of several items of processing equipment, such that if one job takes longer then expected the queue keeps moving by allocating jobs to one of the other items of processing equipment, and
c. **variability buffering** using inventory, capacity and/or time to provide additional resource to offset effects of variability.

3.6.4 Use of Flexible Resources

The use of flexible manning arrangements are becoming increasingly common within manufacturing environments (Daniels and Hoopes 1996, Garud and Kotha 1994) and form an essential requirement for lean manufacturing. The basic idea is to use multi-skilled operators and to move them between tasks depending on where capacity is required. Despite its benefits in dealing with variability, flexible manning schemes can be difficult to implement and depend on organisations being able to:

a. identify areas where additional skills capacity is required,
b. identify what additional skills capacity is needed,
c. identify who will provide the additional skills capacity and from where will they be provided,
d. identify how the additional skills capacity will be generated, and
e. identify when the additional skills capacity is needed.

In manufacturing environments where sources of bottlenecks change frequently it may not be possible to identify where additional skills are required in time to undertake the required training for these bottleneck processes. In flow processing lines with time variability the levels of blocking and waiting change from one TAKT cycle to the next. Hence, flexible manning can be difficult to operate unless designed into the system. This by necessity requires knowledge of the levels of blocking and waiting that are likely to occur.

3.7 Critical Analysis of Past Research

Since the initial work of Hunt (1956) researchers have attempted to determine the effects of variability on the efficiency and effectiveness of flow processing lines. In parallel changes have been occurring in the demands placed on flow processing systems. These demands have tended to accelerate in recent years with the growing use of lean practices to provide the increasing levels of cost, quality, delivery and product choice required to maintain competitive advantage.

When critically examining past research it is necessary to identify how relevant outputs of this research work are to the modern requirements of flow processing lines. In this respect the main changes effecting flow processing systems in recent years are:

a. a reduction in the levels of variability resulting from machine breakdowns, (e.g. through the increasing use of planned maintenance), and product change-overs, (e.g. through the use of such techniques as Single Minute Exchange of Dies) (Section 3.6.2),
b. a reduction in the variability in workstation cycle times arising from operator and work method causes, through the use of such techniques as 5S, standard operations and continuous improvement exercises (Section 3.6),
c. an increase in the levels of variability arising from the need to produce mixed and multi-models on single flow processing lines (Section 3.6.1),

d. the use of lines with long cycle times, i.e. up to 24 hours, in which each workstation contains large numbers of individual processes, amounts of work content and large numbers of operators (Section 1.3),

e. the increase in number of flow processing lines in which buffer stocks between workstations are not possible either because of the cost involved, (particularly with products such as aircraft wings and aero engines), or because output rate and customer lead time dictate both the TAKT time and number of workstations of the flow processing line (Section 1.3), and

f. the increasing use of flexible labour who are able to move between tasks and workstations in conjunction with the ability to design systems that can plan such movements (Section 3.6.4).

Comparison and relevance of the outputs, from previous research, for measuring flow line efficiency to the current needs of flow processing lines can be made in terms of the following areas:

a. the characteristics of flow lines to which they are applicable,
b. the levels and types of variability applicable,
c. the performance metrics used to measure the efficiency of flow lines, and
d. the assumptions under which they are valid.

3.7.1 *Characteristics of Flow lines*

The main characteristics of flow lines examined within previous research are:

i. The number of workstations within the line. This ranged from a minimum of 2 workstations (Hunt 1956, Anderson and Moodie 1968) to a maximum of 20 (Payne, Slack and Wild 1972).
ii. The degree to which buffers are used to offset the effects of variability. Although several researchers examined lines with zero buffer stocks they did so merely to provide benchmarks for comparison with lines with varying levels of non-zero buffers. No detailed investigation of the effects of time variability on flow lines with zero buffers has taken place.
iii. The level of pacing used to control the line.
iv. The degree to which the flow line is balanced in terms of equal allocation of work to workstations

3.7.2 *Levels and Types of Variability Investigated*

Here a narrow range of distribution types have been investigated including normal distributions (Wild and Slack 1973, El-Rayah 1979), exponential distributions (Hunt 1956, Conway et. al. 1988, Hillier and So 1993), and Erlang distributions (Hillier and So 1993). In most cases where specific distributions have been used the authors only suggest that these may be truly representative of the actual distributions.

3.7.3 *Performance Metrics used to Measure Efficiency*

In general performance metrics have been restricted to measuring overall line efficiency in terms of workstation utilisation, levels of work in progress and throughput quantities per time period. No detailed investigation has been undertaken to examine the effects of variability on individual workstations along a flow line such that their relative amounts of blocking and waiting can be estimated. This information is essential if the flexible allocation of workers is to take place along a flow line.

3.7.4 *Assumptions under which Outputs are Valid*

In general the majority of the research was undertaken using flow process lines where it was assumed that:

a. flow lines consist of separate workstations, in a fixed sequence, which perform successive operations on work items as they flow through them,
b. each workstation consists of one production facility,
c. zero, limited or unlimited buffer capacities are allowed to exist between each pair of workstations,
d. workstations may become 'blocked' if unable to move a completed work item to the next workstation, e.g. when the inter-stage buffer between these two workstations has reached its maximum quantity,
e. workstations may need to wait for a work item from a preceding workstations, e.g. when the preceding workstation is still processing and there are no work items in the inter-stage buffer area,

f. the last workstation in the flow line is never blocked, i.e. there is a buffer of infinite capacity waiting to receive its outputs,

g. the first workstation in the flow line never waits for a work item, i.e. it possesses an input buffer which is never empty,

h. each work item enters via the first workstation and remains in the line until completely processed, i.e. until it exits via the last workstation on the line, and

i. that service commences instantaneously when a unit arrives at an empty stage, and units are transferred instantaneously from one stage to the next on the completion of service

Chapter 4 Experimental Design

4.1 Introduction

Greater levels of product and process variability are rapidly becoming an inherent part of the environment under which flow processing lines must operate. The overall effect of this variability is to drastically reduce flow process line efficiency leading to reduced throughput rates and inefficient use of labour and equipment resources.

The **aim of the current research** is to enable high variability flow lines to operate more effectively through enabling the improved use of methods that can help to overcome the detrimental effects of this variability.

The **research objectives** are to examine methods by which the above knowledge may be obtained by the experiments undertaken in :

Main Task 1: Development of a method for combining the individual elements of variability that arise within a workstation into a single variability probability distribution.

Main Task 2: Development of a method for estimating the effects on a flow line of differences in the levels of variability between workstations.

Achieving these research objectives focuses on the need to develop methods for quantitatively measuring the levels of *blocking* and *waiting* that arise within individual workstations as a result of variability.

4.2 Research Methodology

In order to achieve the research objectives it is necessary to obtain data from which the relationships between characteristics of flow processing lines and their individual levels of variability can be quantitatively identified. In this respect, alternatives methods considered during the research are included:

i. Collect data from one or more of the following sources, i.e. existing case studies within the research literature of high variability flow processing lines, direct observation of existing high variability flow processing lines, historical records from existing high variability flow processing lines, questionnaires/interviews using personnel with experience of existing high variability flow processing lines.
ii. Generate data using a suitable modelling technique i.e. discrete event simulation and/or queueing models.

4.2.1 Data Collection Methods

The following data collection methods were considered for use within the research project, i.e.:

i. **Direct observations of existing flow lines.** There are several UK-based flow processing lines, (i.e. Airbus Ltd and Caterpillar BCP), that have sufficient levels of variability to justify their use for data collection purposes. However, this method of data collection was not possible due to the industrial relations problems that would arise in undertaking the lengthy period required to ensure sufficient range of variability was observed during the study. In addition, insufficient resources were available to undertake the study, ie the study would at times require more than one observer to ensure all relevant data at all workstations along the line was collected during each TAKT cycle.

ii. **Published case studies and/or historical data.** A review of the research literature revealed no case studies containing sufficient relevant detail had been published. In addition, both Airbus Ltd and Caterpillar BCP had not maintained operational records in sufficient detail, i.e. for individual TAKT cycles, to make the use of historical data a suitable data collection tool.

iii. **Interviews and/or questionnaires**: Visits were made to both the Airbus Ltd and Caterpillar BCP sites and during these visits informal interviews were carried out with Operations personnel. These interviews focused on determining the amount and degree of detail that could be obtained from the use of more detailed interviews and questionnaires. These initial interviews revealed that insufficient quantitative data could be generated by such techniques that would be sufficiently accurate and precise to ensure validity of any subsequent analysis.

4.2.2 Data Generation Methods

Two main methods were considered for use within the research project, i.e. discrete event simulation (DES) and queueing models. The use of queueing models was discounted because of the complexity of the models required to model the effects of different sources of variability and flow processing lines of up to 20 workstations in length. In addition, the research aims require both the levels of blocking and waiting at individual workstations to be determined. Queueing models measure overall workstation non-utilisation and cannot differentiate between blocking and waiting levels.

The method selected for generating data was, therefore, discrete event simulation. Such systems are flexible in terms of the length of flow lines that can be modelled and the number of variables that are allowed to contribute to the overall variability of individual workstations and of the flow line itself. In addition, individual levels of blocking and waiting arising within workstations could be identified.

4.2.3 Selection of Experimental Methodology

When using discrete event simulation to generate data, care must be taken to ensure that the models used provide suitable data for subsequent analysis. It is, therefore, necessary to choose an appropriate 'design of experiments' technique for selecting which models should be used. Here the main 'design of experiments' candidate methods for selection are:

a. full enumeration by undertaking all possible experiments,

b. partial enumeration using for example Taguchi Orthogonal arrays to decide which models should be selected, and

c. design experiments to isolate each variable such that its individual effect can be identified.

The use of full enumeration was discounted due to the excessively large number of models that would need to be developed. Partial enumeration using Taguchi array was attempted using nine variables (i.e. factors) and with each factor possessing the three values (levels) as shown in Table 4.1. Analysis of the results of these experiments indicated that the Taguchi approach could not provide quantitative measures of the effects on blocking and waiting of individual variables. The primary reason being that variables possessed non-linear relationships in terms of their effects on blocking and waiting and that the use of Taguchi arrays did not allow sufficient levels for each variable that would have been required to establish the true nature of these non-linear relationships.

Factor	Level 1	Level 2	Level 3
set-up time	1 = low i.e.: 1minute	2 = medium i.e.: 25minutes	3 = high i e : 50minutes
process time	1 = low i.e.: 15minute	2 = medium i.e.: 25minutes	3 = high i.e.: 50minutes
batch size	1 = low i.e : 1 part	2 = medium i.e.:30parts	3 = high i.e.: 50parts
rework level	1 = low i.e.: 1 percentage	2 = medium i.e.: 5 percentage	3 = high i e.: 9 percentage
rework process	1 = recycle from start of the line	2 = recycle at the same workstation	3 = scrap
long breakdown	1 = low i.e.: 50minute	2 = medium i.e.: 100minutes	3 = high i.e.: 150minutes
short stoppage	1 = low i.e.: 1minute	2 = medium i e.: 5minutes	3 = high i.e.: 9minutes
position of workstation with variability	1 = at the front of the line	2 = middle of the line	3 = at the end of the line
number of workstation with variability	1 = low i.e.: 1 workstation	2 = medium i.e.: 2 workstations	3 = high i.e.: 3 workstations

Table 4.1: Taguchi L27-a Orthogonal Array

The experimental methodology then focussed on designing suitable experiments that would isolate individual variables such that their individual effects could be identified.

In all experiments no 'warm up' period was included prior to the start of the collection of blocking and waiting results since the actual time for the flow processing line to fill up represent only 0.63% the total simulation run time of 20,000 time units. That is, the largest model was 21 workstations in length with a maximum of 6 time units per workstation. Hence, the flow line would be full in 126 time units, (i.e. 21x6), representing 0.63% of total simulation run time (i.e. 126/20,000).

For each experiment only one simulation run was performed with all experimental runs using the same random number stream. It was decided that multiple runs for each expermeint using different random number streams was not desirable since this would tend to provide a false impression of the accuracy of results, i.e.: use of triangular distribution already reduces the levels of accuracy

4.3 Methodology and Experimental Design

The methodology is divided into 2 main tasks, i.e.:

> **Main Task 1:** Development of a method for combining the individual elements of variability that arise within a workstation into a single variability probability distribution.
>
> **Main Task 2:** Development of a method for estimating the effects on a flow line of differences in the levels of variability between workstations.

4.3.1 Main Task 1

This main task is composed of the following sequence of steps. Tests have been included, where appropriate, in order to determine the validity of individual steps.

Step 1: Selecting the Distribution Type

The various types of probability distributions applicable to manufacturing have been identified in Section 3.3 and the Triangular distribution chosen as the basic distribution for use in this experimentation. Essentially Triangular distributions have been selected for measuring variability since these distribution types are often used, particularly within project management, when the actual probability distribution types are unknown. The primary reason for this is the relative ease with which the three values that define the triangular distribution can be subjectively estimated. Although providing approximations of other distribution types the triangular distribution is flexible in being able to approximate a wide range of such distributions including both skewed and non-skewed distribution types.

Let the variability associated with the individual task cycle times (TCT) be represented by the triangular distribution shown in Figure 4.1 then the mode is represented by the most likely t_{TCT} and the median, mean and standard deviation of the triangular distribution can be calculated using equations 3 to 6 , i.e.:

If $t_{TCT} - a_{TCT} \geq 0.50(b_{TCT} - a_{TCT})$ then

$$\text{Median} = a_{TCT} + \sqrt{0.50(t_{TCT} - a_{TCT})(b - a)} \tag{3}$$

If $t_{TCT} - a_{TCT} < 0.50(b_{TCT} - a_{TCT})$ then

$$\text{Median} = b_{TCT} - \sqrt{0.50(b_{TCT} - a_{TCT})(b_{TCT} - t_{TCT})} \tag{4}$$

$$\text{Mean} = \frac{a_{TCT} + t_{TCT} + b_{TCT}}{3} \tag{5}$$

$$\text{Standard Deviation} = \sqrt{\frac{a_{TCT}^2 + t_{TCT}^2 + b_{TCT}^2 - a_{TCT}t - a_{TCT}b_{TCT} - t_{TCT}b_{TCT}}{18}} \tag{6}$$

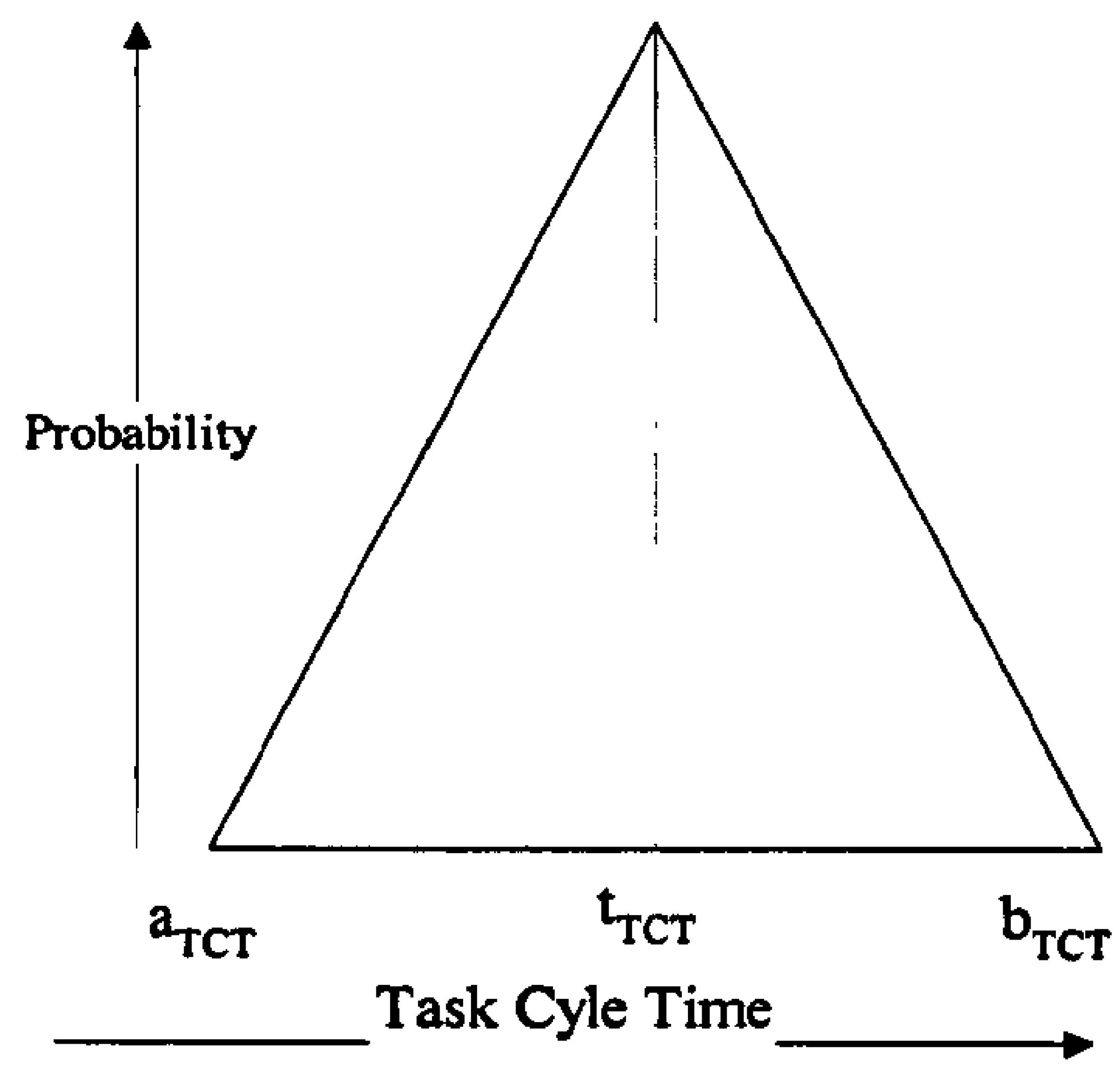

Figure 4.1: Distribution of Task Cycle Times

Where:

a_{TCT} = shortest likely time required to complete a task,
b_{TCT} = longest likely time required to complete a task, and
t_{TCT} = most likely time required to complete a task.

The categories identified by Hopp and Spearman (1996) have been used to classify the basic types of variability occurring within flow processing lines as follows:

i. Task Cycle times, i.e. the times required for an operator or item of processing equipment to complete work allocations.

ii. Short stoppages, i.e. these represent the variety of events, such as equipment change-overs, that cause minor stoppages within flow processing lines.

iii. Long stoppages, i.e. these represent the variety of events, such as major equipment breakdowns that cause major disruptions and stoppages in flow line operations.

Step 2: Selecting the Experimental Testing Tool

The computer-based simulation modelling package Simul8 was selected for use in performing the experimental tests required to validate the individual steps involved in the proposed methodology, and generating data from which to derive models for estimating levels of blocking and waiting arising from differences in workstation variability levels. This simulation package had the functionality to model all simulation models required within the experimentation.

Step 3: Let the variability associated with the times between the occurrences of short stoppages, denoted as the SSTBO, be represented by Figure 4.2 and the variability associated with the durations of these short stoppages (SSD) be represented by Figure 4.3.

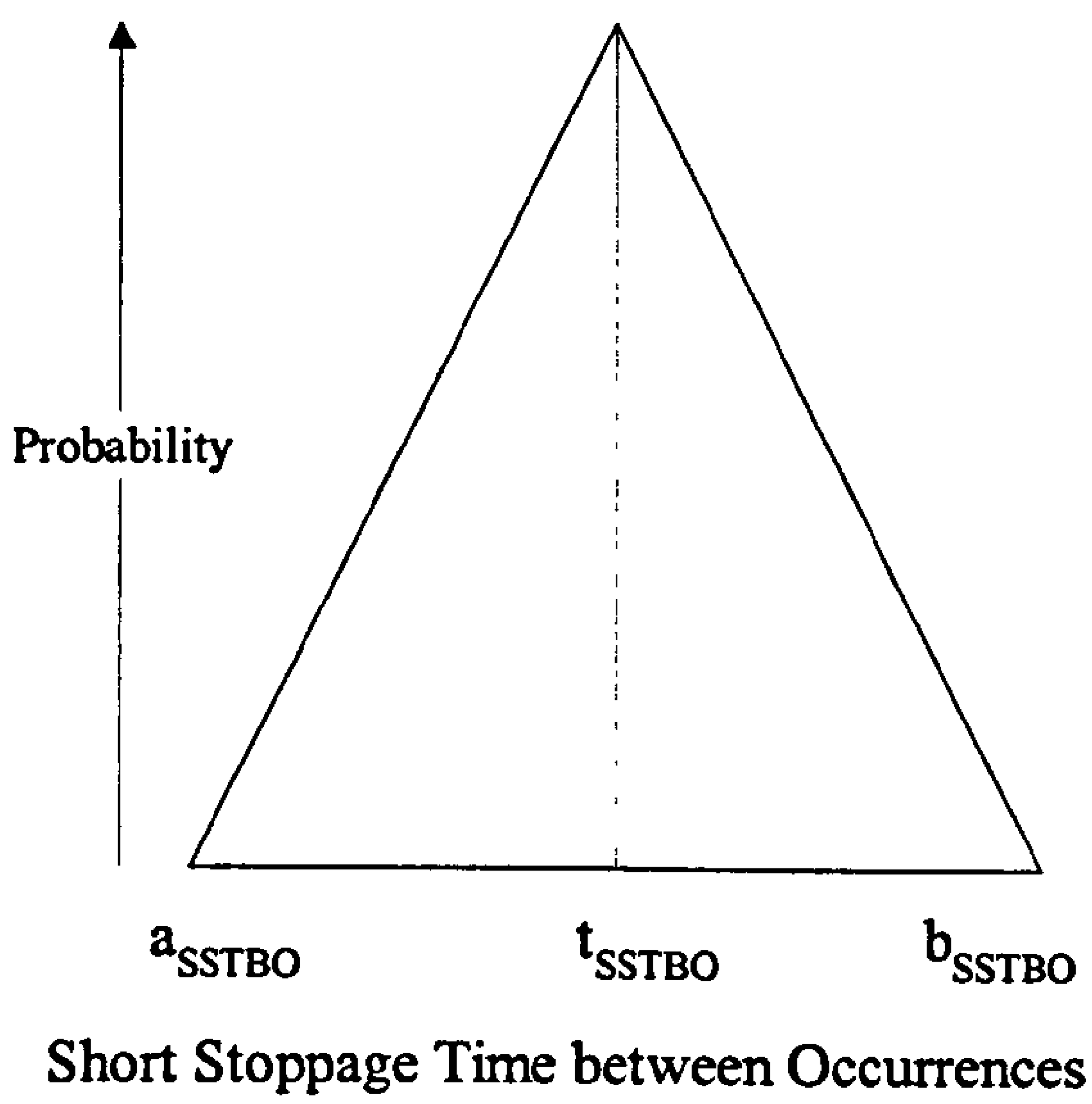

Figure 4.2: Distribution of Times between Occurrences of Short Stoppages

Where:

a_{SSTBO} = the shortest likely time between occurrences of short stoppages,
b_{SSTBO} = the longest likely time between occurrences of short stoppages, and
t_{SSTBO} = the most likely time between occurrences of short stoppages.

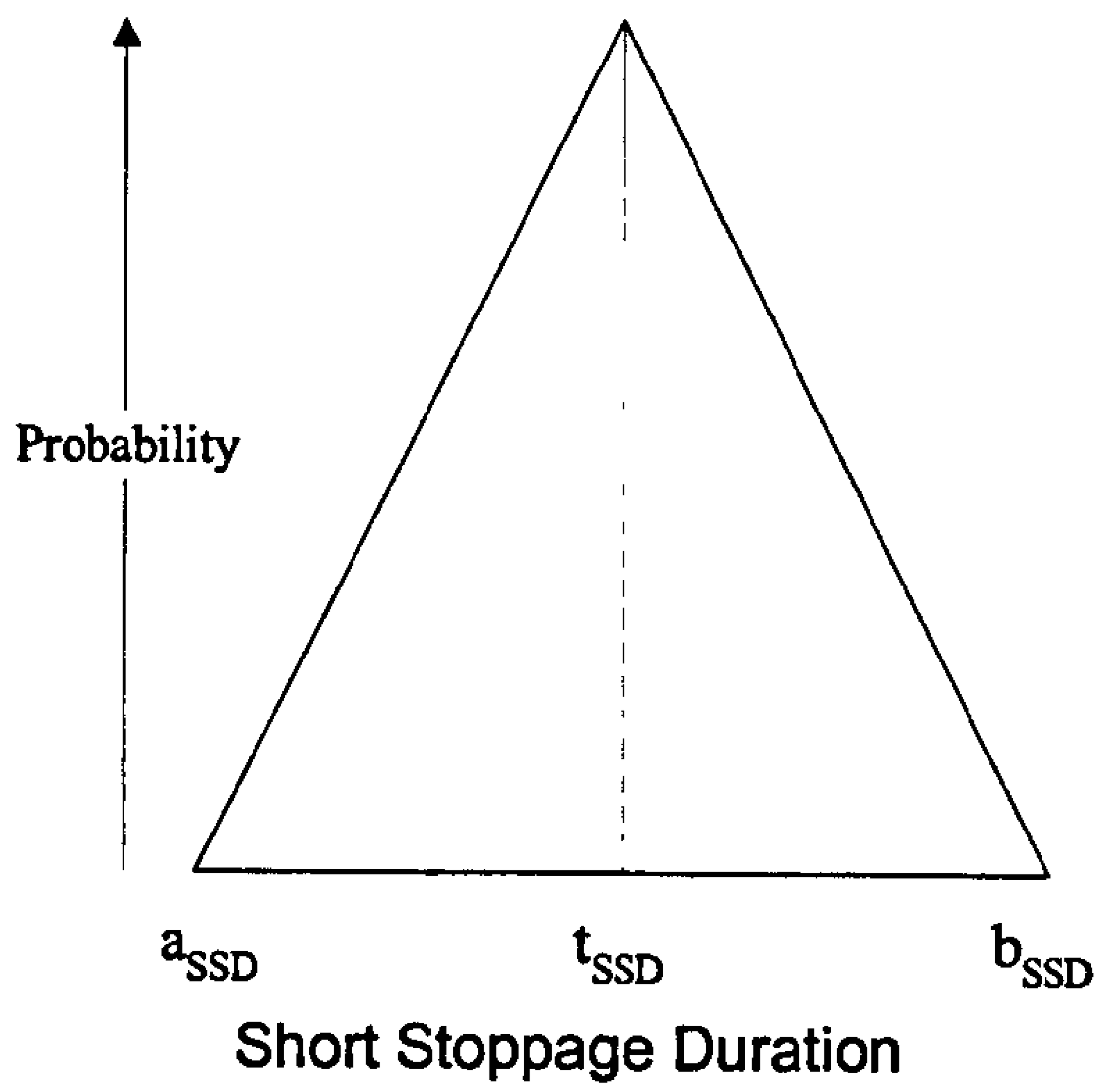

Figure 4.3: Distribution of Time Durations of Short Stoppages

Where:

a_{SSD} = the shortest likely time duration of a short stoppage,
b_{SSD} = the longest likely time duration of a short stoppage, and
t_{SSD} = the most likely time duration of a short stoppage.

Step 4: Let the variability associated with the times between the occurrences of long stoppages (LSTBO) be represented by Figure 4.4 and the variability associated with the durations of these long stoppages (LSD) be represented by Figure 4.5.

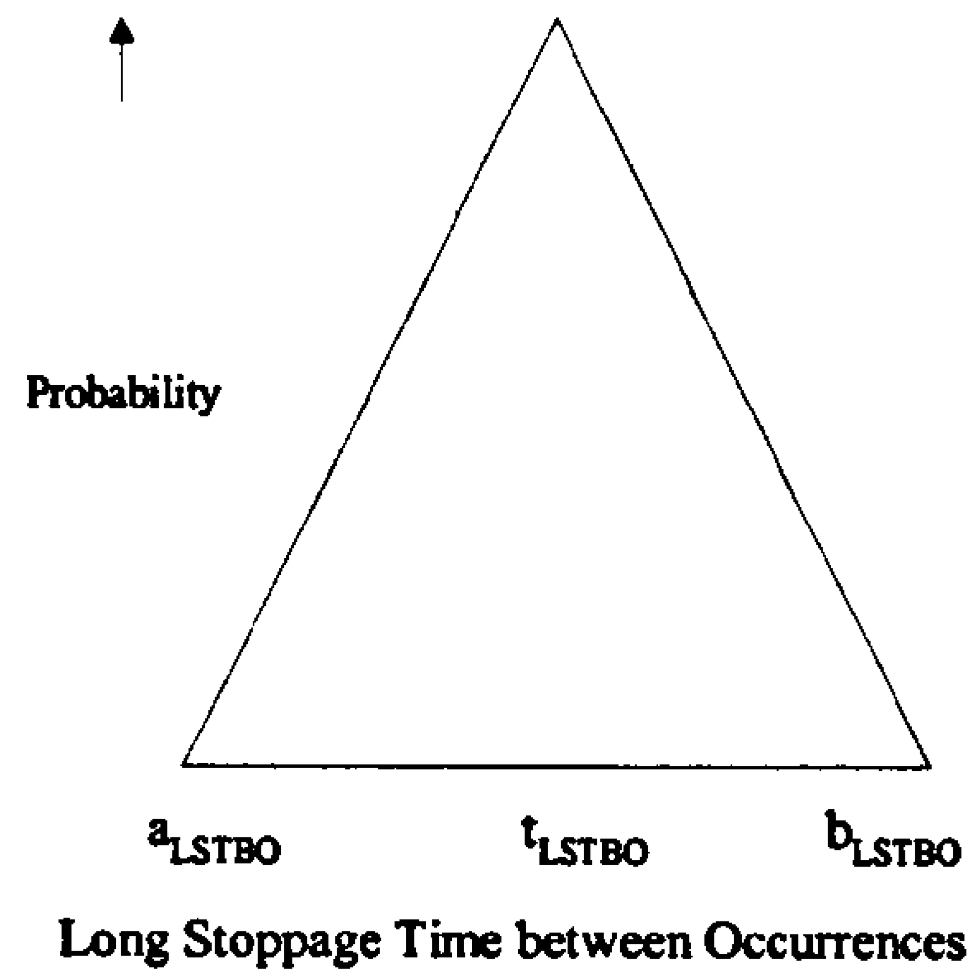

Figure 4.4: Distribution of Times between Occurrences of Long Stoppages

Where:

a_{LSTBO} = the shortest likely time between occurrences of long stoppages,
b_{LSTBO} = the longest likely time between occurrences of long stoppages, and
t_{LSTBO} = the most likely time between occurrences of long stoppages.

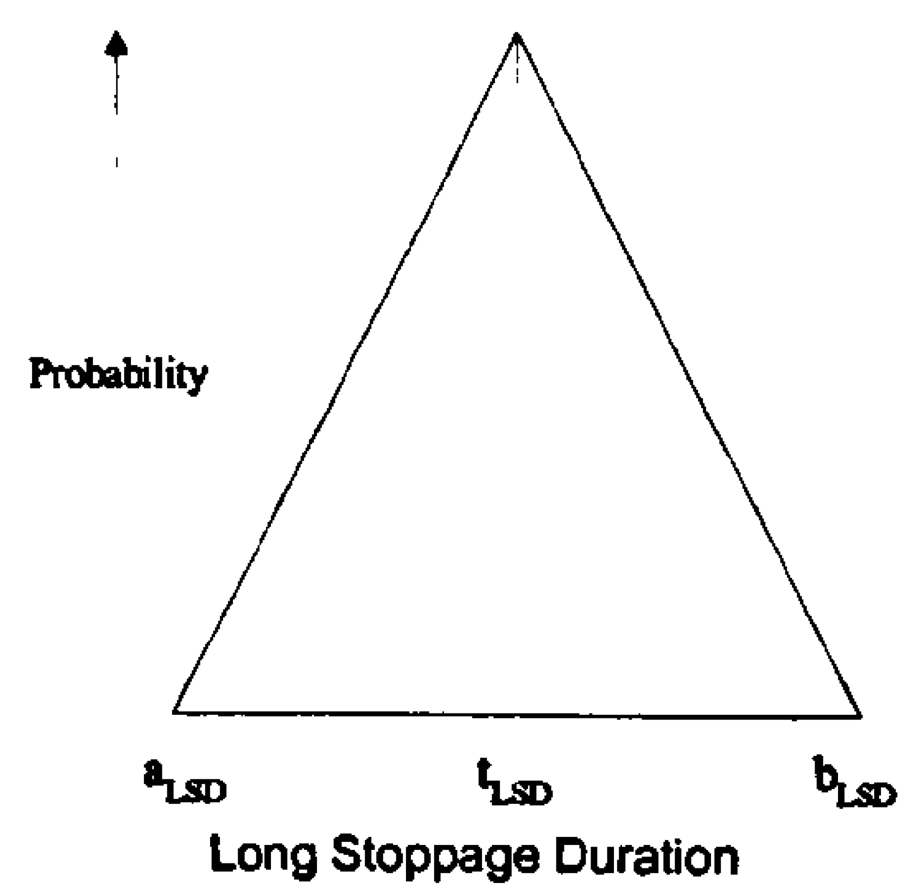

Figure 4.5: Distribution of Time Durations of Long Stoppages

Where:

a_{LSD} = the shortest likely time durations of long stoppages,
b_{LSD} = the longest likely time durations of long stoppages, and
t_{LSD} = the most likely time durations of long stoppages.

Step 5: Extend the use of the 'availability' equation developed by Hopp and Spearman (1996) to develop triangular distributions for both Short Stoppage (SSA) and Long Stoppage availabilities (LSA), i.e.:

(i) For short stoppages the three values of the 'availability' triangular distribution shown in Figure 4.6 are calculated as follows:

$$a_{SSA} = a_{SSTBO} \cdot (b_{SSTBO} + b_{SSD})^{-1} \quad (7)$$

$$b_{SSA} = b_{SSTBO} \cdot (b_{SSTBO} + a_{SSD})^{-1} \quad (8)$$

$$t_{SSA} = t_{SSTBO} \cdot (t_{SSTBO} + t_{SSD})^{-1} \quad (9)$$

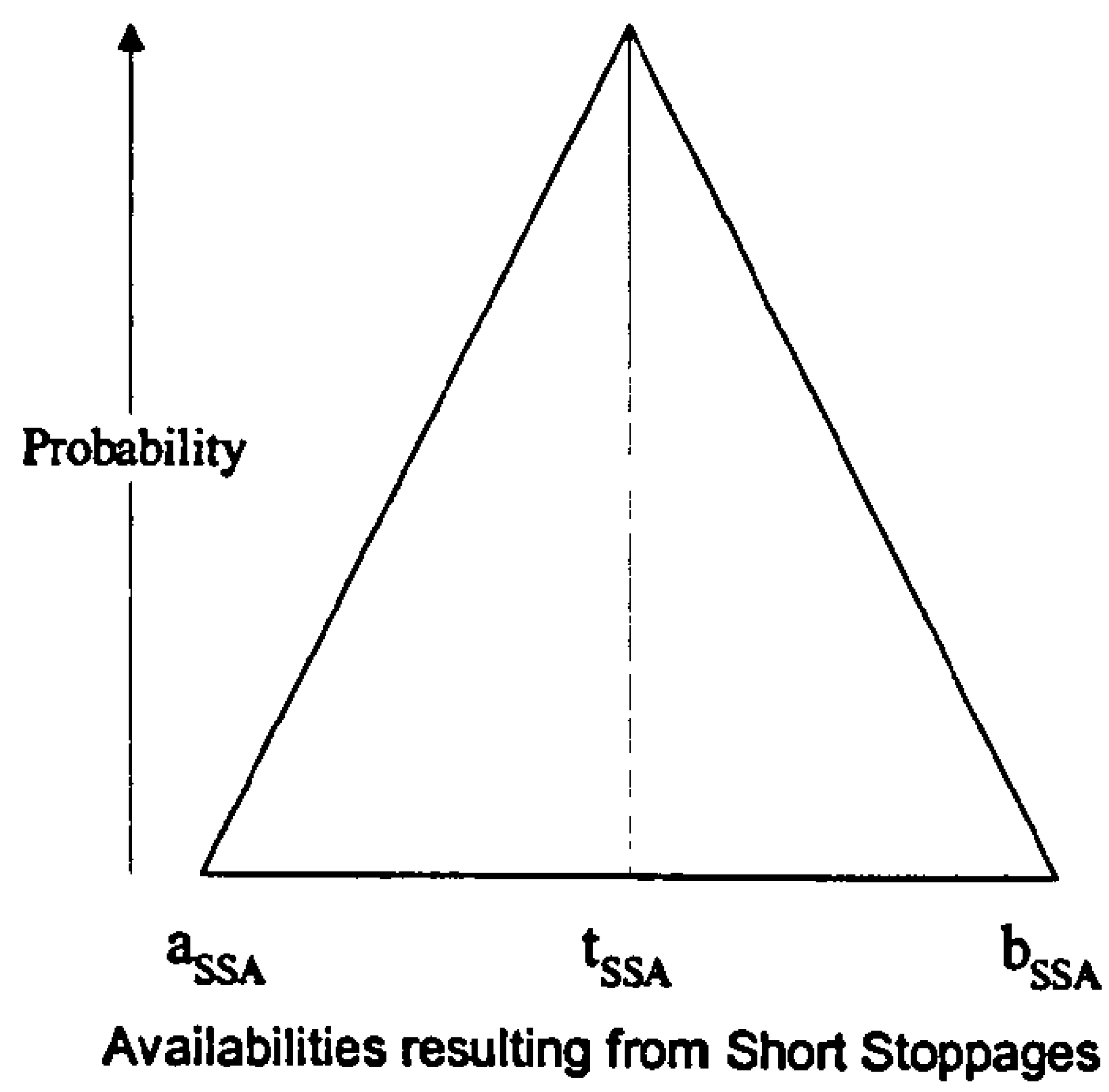

Figure 4.6: Distribution of Availabilities resulting from Short Stoppages

Where:

a_{SSA} = least level of availability resulting from the occurrence of short stoppages,
b_{SSA} = greatest level of availability resulting from the occurrence of short stoppages, and
t_{SSA} = most likely level of availability resulting from the occurrence of short stoppages.

(ii) For long stoppages the values of the 'availability' triangular distribution shown in Figure 4.7 are calculated as follows:

$$a_{LSA} = a_{LSTBO} \cdot (a_{LSTBO} + b_{LSD})^{-1} \quad (10)$$

$$b_{LSA} = b_{LSTBO} \cdot (b_{LSTBO} + a_{LSD})^{-1} \quad (11)$$

$$t_{LSA} = t_{LSTBO} / (t_{LSTBO} + t_{LSD})^{-1} \quad (12)$$

Where:

a_{LSA} = least level of availability resulting from the occurrence of long stoppages,
b_{LSA} = largest level of availability resulting from the occurrence of long stoppages, and
t_{LSA} = most likely level of availability resulting from the occurrence of long stoppages.

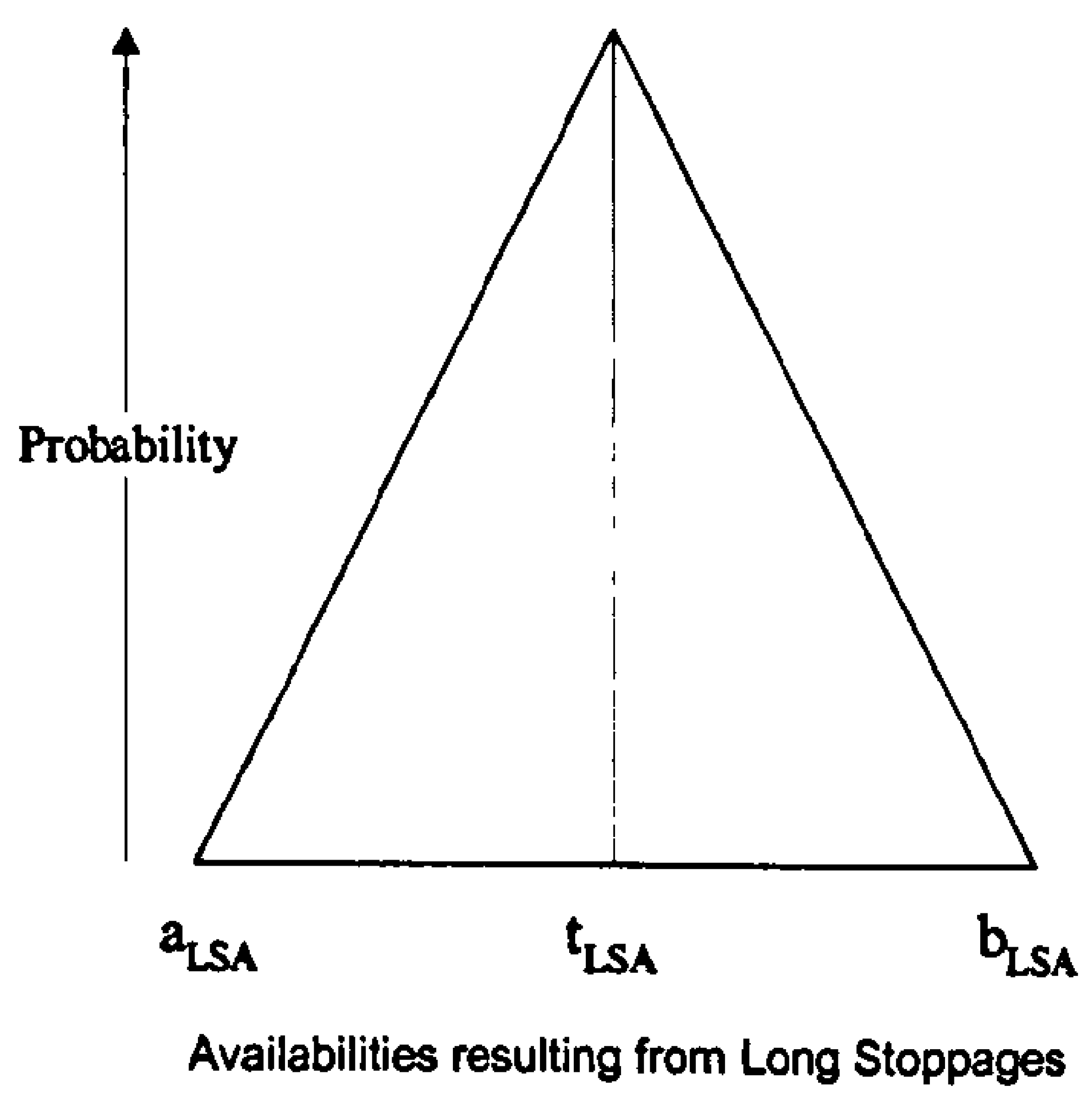

Figure 4.7: Distribution of Availabilities resulting from Long Stoppages

Test 1: Simulation models were constructed to test the validity of Equations 7, 8 and 9 to develop the availability distribution shown in Figure 4.6. Each model consisted of a single workstation Simul8 modelling element with 'machine breakdowns' used to represent short stoppages. A series of experiments were performed in which cycle times, mean time to occurrence of a breakdown and mean duration of the breakdown were varied as shown in Table 4.1. From the results of these simulations values for a_{SSA}, b_{SSA} and t_{SSA} were obtained and compared with values calculated using Equations 7, 8 and 9.

TAKT Time	Short Stoppages					
	Time between occurrences			Duration		
	a	t	b	a	t	b
1	10	30	60	1	2	3
1	10	30	60	2	5	6
1	10	30	60	3	4	6
1	10	30	60	1	3	6
1	10	30	60	3	4	5
1	10	20	30	2	5	6
1	5	10	15	3	4	6
1	10	20	30	1	2	3
1	15	30	45	1	3	6
10	10	30	60	1	2	3
10	10	30	60	2	5	6
100	10	30	60	1	2	3
100	10	30	60	2	5	6

Table 4.2: Experiments to test Short Stoppage Availability Equations 7, 8 and 9

Test 2: Simulation models were constructed to test the validity of Equations 10, 11 and 12 to develop the availability distribution shown in Figure 4.7. Each model consisted of a single workstation with 'machine breakdowns' used to represent long stoppages.

A series of experiments was performed in which cycle times, mean time to occurrence of a breakdown and mean duration of the breakdown were varied as shown in Table 4.2. From the results of these simulations values for a_{LSA}, b_{LSA} and t_{LSA} were obtained and compared with values calculated using Equations 10, 11 and 12.

TAKT Time	Long Stoppages					
	Time between occurrences			Duration		
	a	t	b	a	t	b
1	20	40	80	10	20	30
1	20	40	80	10	40	50
1	20	40	80	10	40	60
1	20	40	80	20	30	50
1	20	40	80	20	30	40
1	20	40	80	30	40	50
1	20	40	80	30	50	60

Table 4.3: Experiments to Test Long Stoppage Availability Equations

Step 6: Use the 'availability' distribution resulting from Short Stoppages shown in Figure 4.6 to convert the distribution of task cycle times, (i.e. Figure 4.1), into a distribution of 'effective' task cycle times, i.e. task times that would arise due to the occurrence of short stoppages. This is achieved using Equations 13, 14 and 15 to produce the distribution shown in Figure 4.8.

$$a_{ECT\_SS} = a_{TCT} \cdot b_{SSA}^{-1} \tag{13}$$

$$b_{ECT\_SS} = b_{TCT} \cdot a_{SSA}^{-1} \tag{14}$$

$$t_{ECT\_SS} = t_{TCT} \cdot t_{SSA}^{-1} \tag{15}$$

Where:

a_{ECT_SS} = the shortest likely effective task cycle time resulting from the effect of short stoppages,

b_{ECT_SS} = the longest likely effective task cycle time resulting from the effect of short stoppages, and

t_{ECT_SS} = the most likely effective task cycle time resulting from the effect of short stoppages.

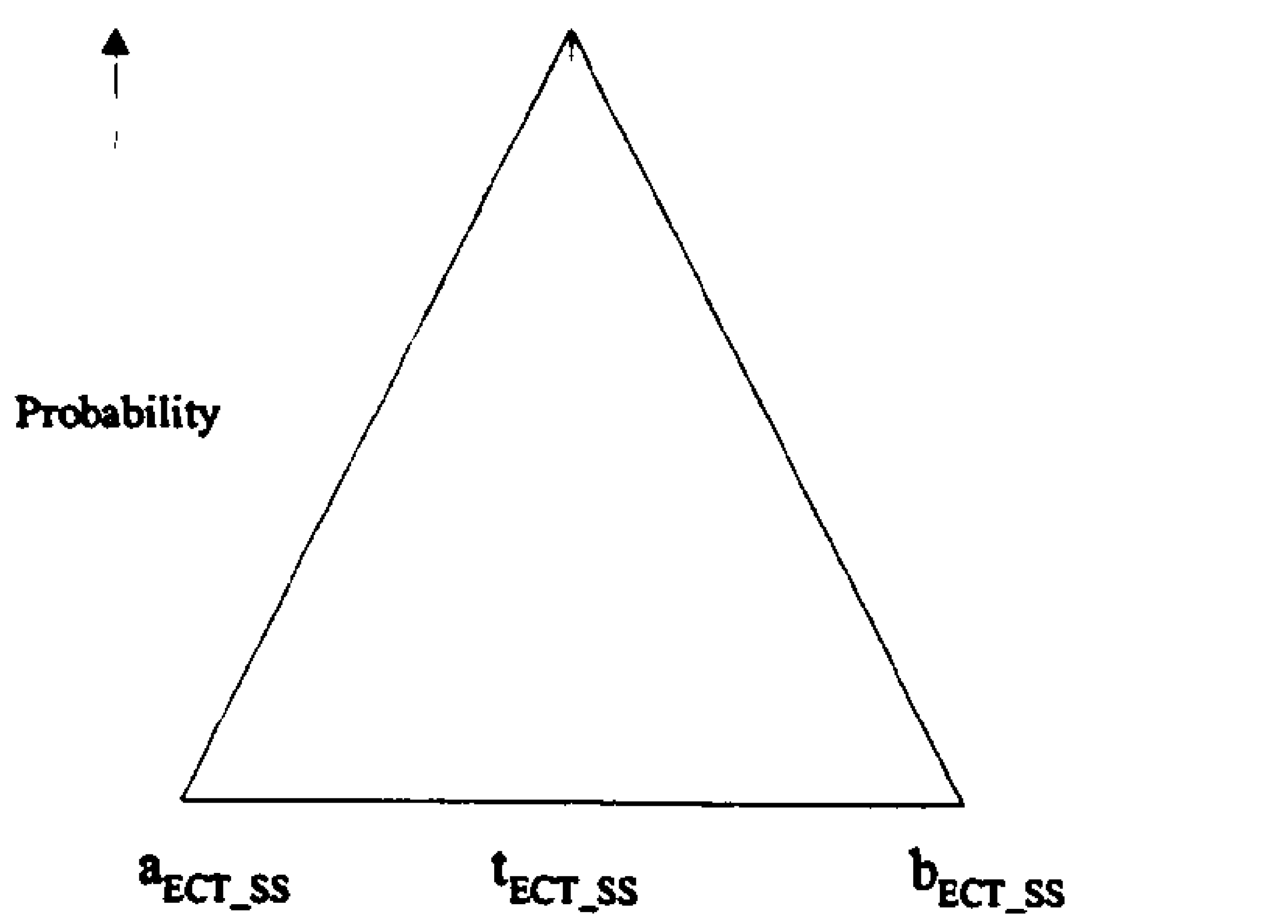

Figure 4.8: Distribution of Effective Task Cycle Times resulting from Short Stoppages

Test 3: Simulation models were constructed to test the validity of employing Equations 13, 14 and 15 to determine effective task times. These models were used to carry out the series of experiments listed in Table 4.3. From the results of these tests, values for a_{ECT_SS}, b_{ECT_SS} and t_{ECT_SS} were obtained and compared with values calculated using Equations 13, 14 and 15.

Task Cycle Times			Results from Short Stoppage Availability Equations		
a	**t**	**b**	a_{SSA}	t_{SSA}	b_{SSA}
1	3	5	0.77	0.94	0.98
1	3	6	0.63	0.86	0.97
1	3	4	0.63	0.88	0.95
2	3	5	0.63	0.91	0.98
2	3	6	0.67	0.88	0.95
1	3	5	0.77	0.94	0.98
1	3	6	0.63	0.8	0.9
1	3	4	0.45	0.71	0.83
2	3	5	0.71	0.91	0.98
1	3	5	0.77	0.94	0.98
1	3	6	0.63	0.86	0.97
1	3	5	0.77	0.94	0.98
1	3	6	0.63	0.86	0.97

Table 4.3: Experiments to test the Effect of Short Stoppage Availability on Effective Cycle Task Times

Step 7: Use the 'availability' distribution resulting from Long Stoppages shown in Figure 4.7 to modify the distribution of effective task cycle times resulting from Short Stoppages, (i.e. Figure 4.8), to include the effect of Long Stoppages. This distribution would, therefore, represent the effective task cycle times that would arise due to the occurrence of both Short and Long stoppages. This is achieved using Equations 16, 17 and 18 to produce the distribution shown in Figure 4.9.

$$a_{ECT\_SS\&LS} = a_{ECT\_SS} \cdot b_{LSA}^{-1} \tag{16}$$

$$b_{ECT\_SS\&LS} = b_{ECT\_SS} \cdot a_{LSA}^{-1} \tag{17}$$

$$t_{ECT\_SS\&LS} = t_{ECT\_SS} \cdot t_{LSA}^{-1} \tag{18}$$

Where:

$a_{ECT\_SS\&LS}$ = the shortest likely effective task cycle time resulting from the combined effects of long and short stoppages,

$b_{ECT\_SS\&LS}$ = the longest likely effective task cycle time resulting from the combined effects of long and short stoppages, and

$t_{ECT\_SS\&LS}$ = the most likely effective task cycle time resulting from the combined effects of long and short stoppages.

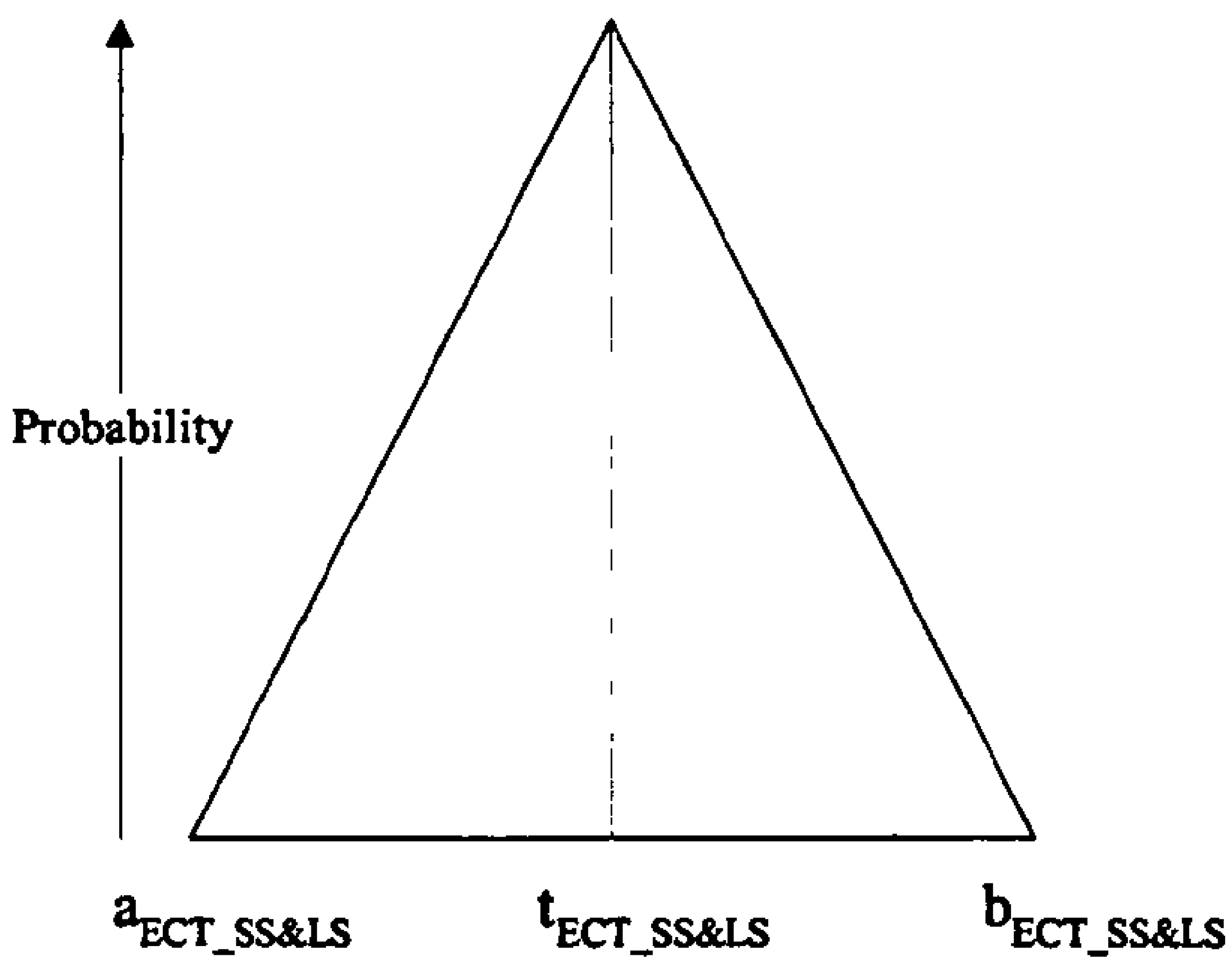

Figure 4.9: Distribution of Effective Task Cycle Times resulting from Short and Long Stoppages

Test 4: Simulation models were constructed to test the validity of employing Equations 16, 17 and 18 to modify the effective task cycle times resulting from Short Stoppages. These models were used to carry out the series of experiments listed in Table 4.4. From the results of these simulations values for $a_{ECT\_SS\&LS}$, $b_{ECT\_SS\&LS}$ and $t_{ECT\_SS\&LS}$ were obtained and compared with values calculated using Equations 16, 17 and 18.

Results from Short Stoppage Effective Task Cycle Time Equations 13, 14 & 15			Results from Long Stoppage Availability Equations 16, 17 & 18		
a_{CE_SS}	t_{CE_SS}	b_{CE_SS}	a_{LSA}	t_{LSA}	b_{LSA}
1.02	3.30	6.67	1.20	5.07	7.84
1.03	3.53	9.84	1.24	7.51	11.85
1.05	3.49	6.45	1.28	7.27	7.87
2.03	3.33	8.06	2.61	6.06	10.34
2.10	3.49	9.23	2.69	6.23	11.83

Table 4.4: Experiments to test Effect of Long Stoppage Availability on Effective Task Cycle Times

Step 8: Use the PERT technique to determine total workstation effective cycle time variability i.e. Figure 4.10, arising from the variability of the individual sequential tasks allocated to a workstation.

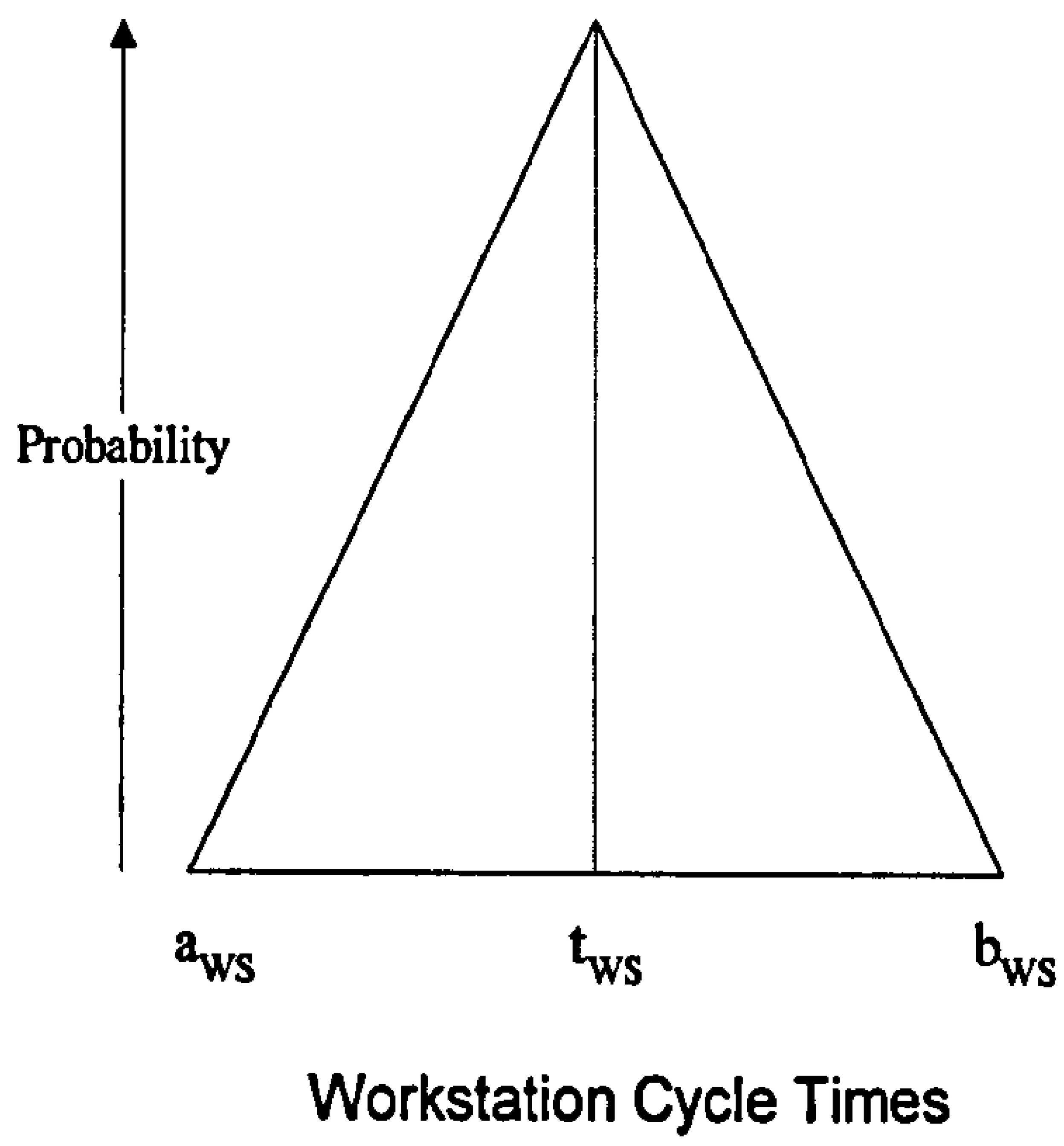

Figure 4.10: Distribution of Workstation Cycle Times

This is achieved using the following equations:

$$a_{WS} = \sum_{i=1}^{i=n} a_i \tag{19}$$

$$b_{WS} = \sum_{i=1}^{i=n} b_i \tag{20}$$

$$t_{WS} = \sum_{i=1}^{i=n} t_i \tag{21}$$

Where:

a_{WS} = the shortest effective workstation cycle time,
b_{WS} = the longest effective workstation cycle times,
t_{WS} = the most likely effective workstation cycle times,
n = number of individual tasks allocated to the workstation,
a_i = $a_{ECT\_SS\&LS}$ for task *i*,
b_i = $b_{ECT\_SS\&LS}$ for task *i*, and
t_i = $t_{ECT\_SS\&LS}$ for task *i*.

Test 5: Simulation models were constructed to test the validity of employing the PERT technique, i.e. as represented by Equations 19, 20 and 21, to determine total workstation cycle times. These models were used to carry out the series of experiments listed in Table 4.5. From the results of these simulations values for a_{WS}, b_{WS} and t_{WS} were obtained and compared with values calculated using Equations 19, 20 and 21.

Work Station Number	Task Number	Task Cycle Times		
		$a_{ECT\_SS\&LS}$	$t_{ECT\_SS\&LS}$	$b_{ECT\_SS\&LS}$
1	1	1	3	4
	2	2	3	5
	3	2	3	6
Workstation 1 Total =		5	9	15

Work Station Number	Task Number	Task Cycle Times		
		$a_{ECT\_SS\&LS}$	$t_{ECT\_SS\&LS}$	$b_{ECT\_SS\&LS}$
2	1	2	3	4
	2	1	3	5
	3	1	3	6
	4	0	3	4
	5	0	3	5
	6	0	3	6
Workstation 2 Total =		4	18	30

Table 4.5: Experimentation to test use of PERT Methodology to calculate Workstation Cycle Times

4.4 Main Task 2

The aim of Main Task 2 is to make use of workstation cycle time variability distributions to develop models by which the effects on the flow line of differences in workstation variability can be determined. The essential question to be answered is illustrated in Figure 4.11, i.e. how do differences in levels of variability between workstations affect the levels of blocking and waiting experienced by individual workstations along the flow line.

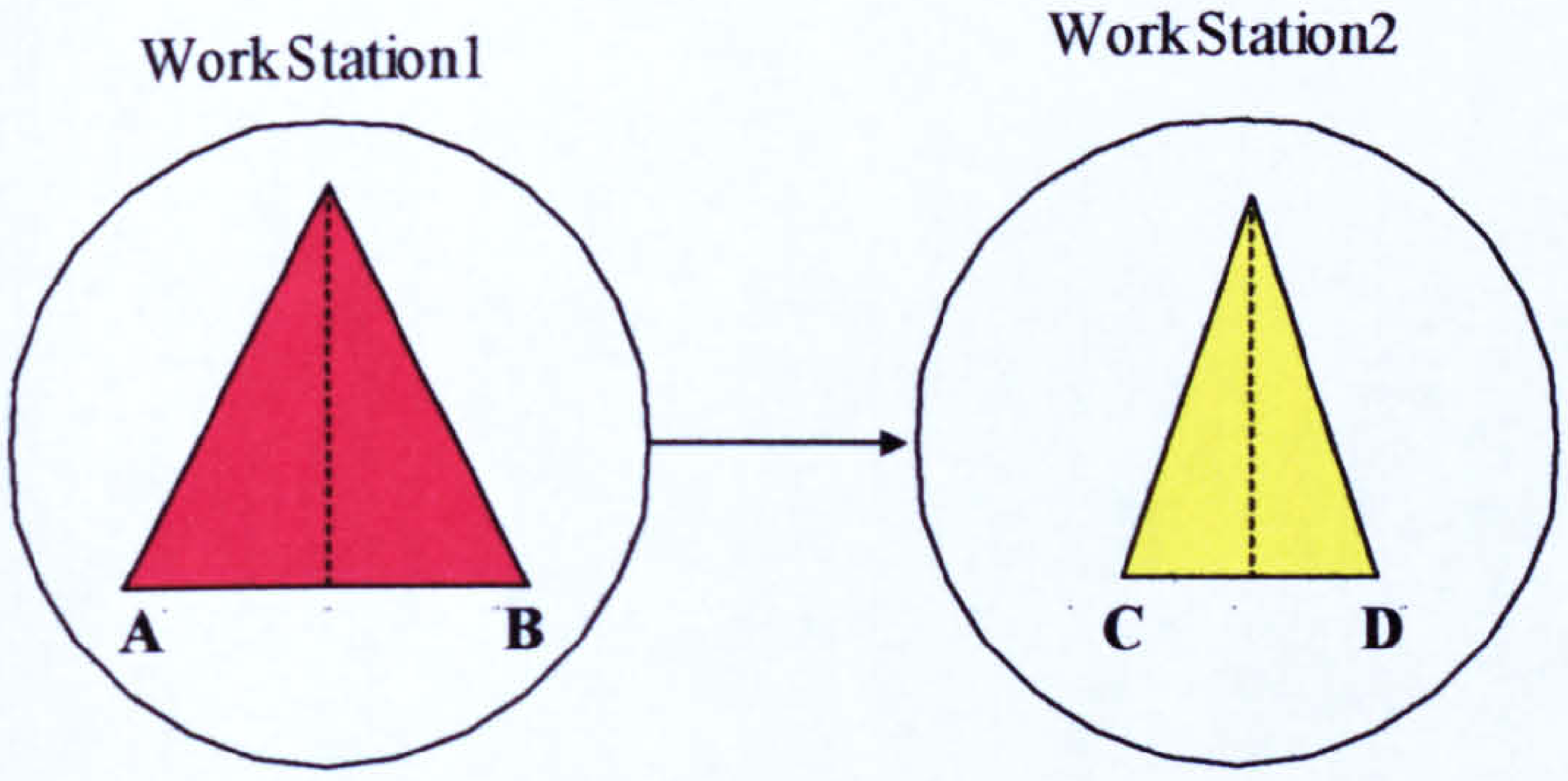

Figure 4.11: Sequential Workstations of Flow Line Showing Differences in Workstation Variability

Step 1: Categorise individual levels of variability in order to assist in identification of the types of relationships that exist between workstations, i.e. here two methods were identified:

i. Using the maximum range of variability employed within the trials carried out in Main Task 1, i.e. 0 to 6 time units, the various shapes of the variability distributions were categorised as illustrated in Figure 4.12. Here there are 15 types categorised according to the values of their shortest (a), longest (b) and most likely (t) times.

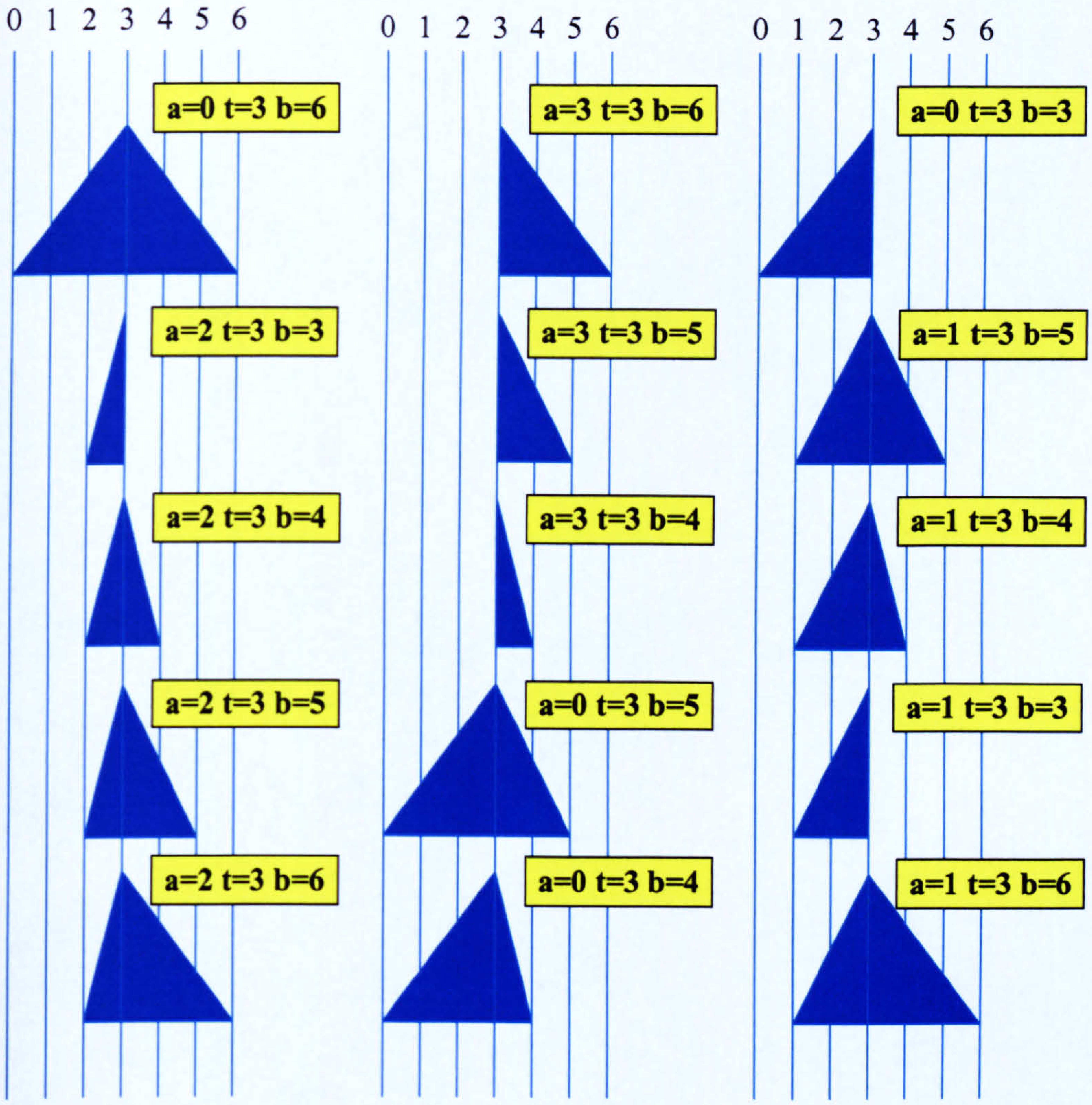

Figure 4.12: Categories of Probability Distributions

ii. Categorise variability according to the relative levels of variability that exist i.e. let AB and CD represent the range of variability of sequential workstations as shown in Figure 4.11. Eleven relationships can then be identified, as shown in Figure 4.13, that the values of A, B, C and D can take if it is assumed that the modes of the probability distributions of both workstations remain equal, (i.e. representing a balanced flow line), and that at all times A < B and C < D. From these figures the individual areas of each probability distribution causing either blocking, waiting or both blocking and waiting can be identified.

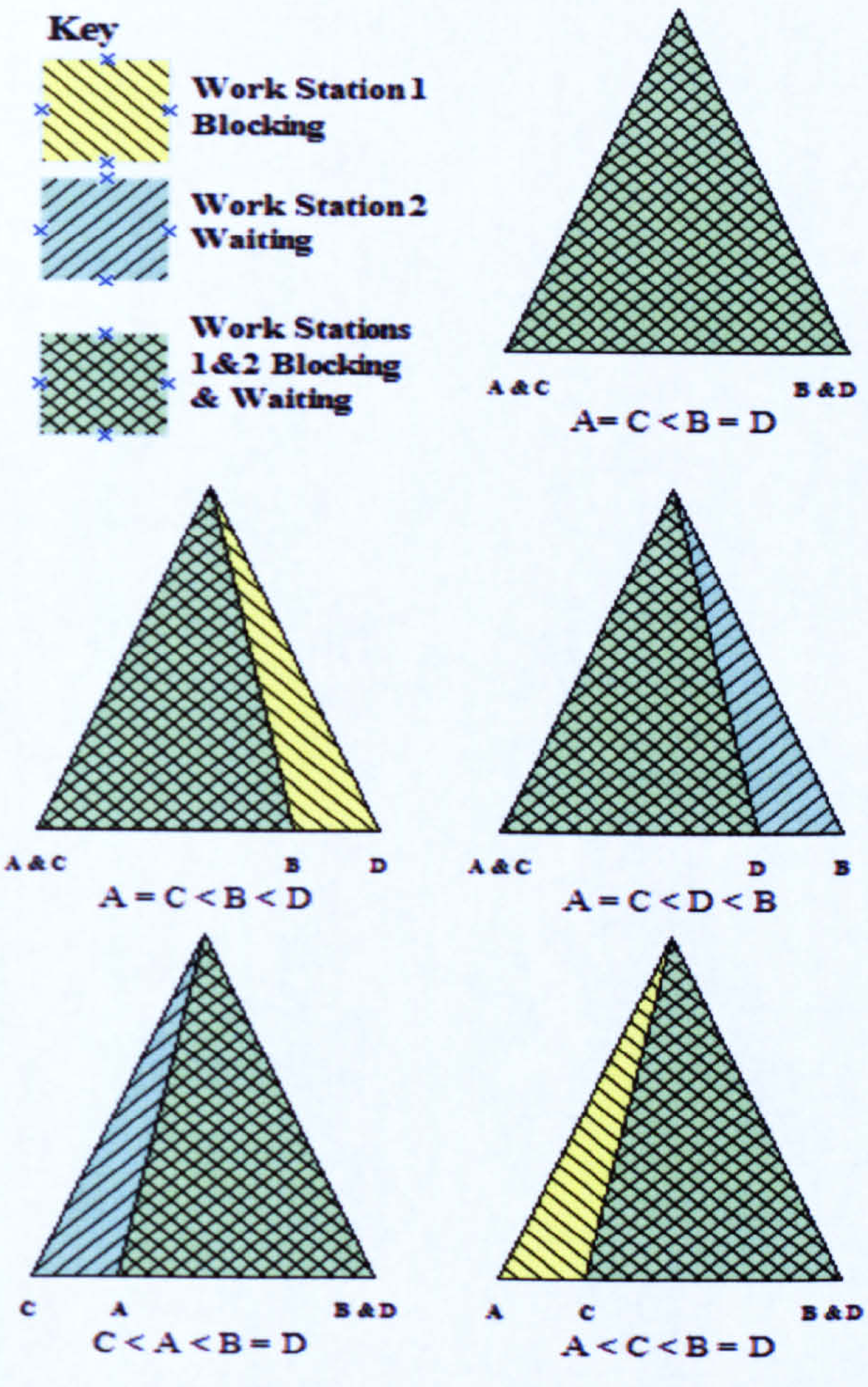

Figure 4.13: Basic Relationships between Sequential Probability Distributions

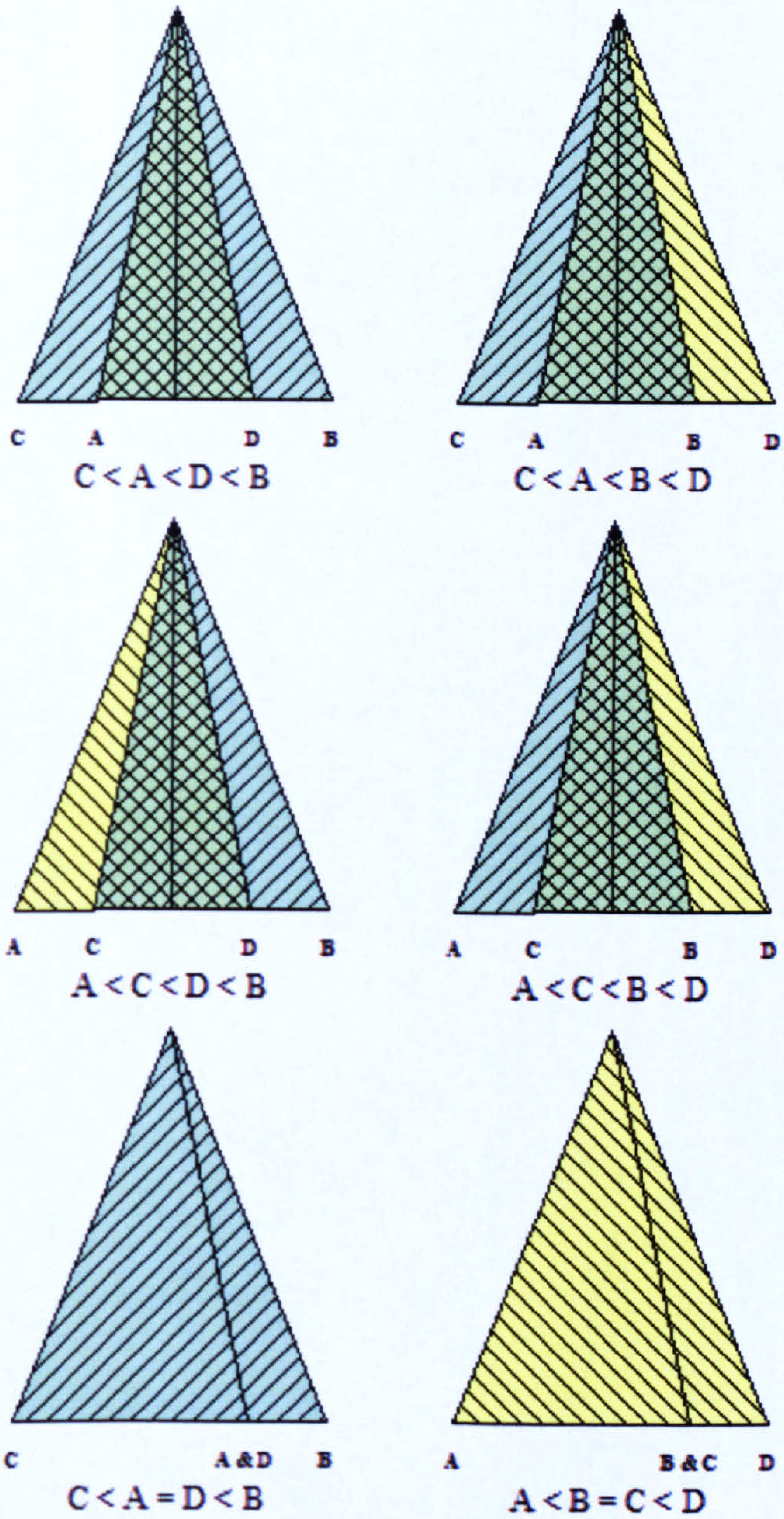

Figure 4.13 Continued: Basic Relationships between Sequential Probability Distributions

Trials 1: These trials were designed to identify the basic manner in which %Blocking and %Waiting of individual workstations varied along a flow line. Simulation models were developed to examine two basic types of flow line, i.e.:

a. Flow lines in which each workstation exhibited the same level of variability, i.e. a range of variability distributions were examined of which *a=3:t=3:b=4* and *a=0:t=3:b=6* represented the highest and lowest levels within the categories selected for investigation. For each of the workstation distributions selected flow lines of 2, 3, 5, 8, 13 and 21 workstations in length were examined.
b. Flow lines in which one or more workstations exhibited differing levels of variability, i.e. a range of variability distributions were examined of which *a=0:t=3:b=6* and *a=0:t=3:b=3* provided both differences in levels of variability but common start points. For each of these workstation distributions flow lines of 5, 7 and 9 workstations in length were examined with the position varying along the line of the workstation exhibiting the differing level of variability.

Trials 2: These trials were designed to identify the effect of levels of variability on workstation blocking and waiting. For each of the variability categories shown in Figure 4.12 two-workstation flow lines were simulated in which each workstation possessed the same level of variability. Two-workstation flow lines were chosen in order to remove the effects of both number of workstations within a line and the position of a workstation within the line. Common levels of variability were chosen to remove the effects of variability differences between successive workstations. Workstation %Blocking and %Waiting levels arising from the simulation models were compared with variability means, geometric means, harmonic means, PERT means, standard deviations and coefficient of variations of the workstation cycle time variability distributions.

Trials 3: These trials were designed to identify the relationships between %Blocking and %Waiting of the 'number of workstations within a flow line' and the 'position of an individual workstation along the line'. Here trials involved simulating flow lines of varying length for each of the variability categories shown in Figure 4.12. Flow lines examined all exhibited common levels of variability at each workstation along the line and were of 2, 3, 5, 8, 13 and 21 workstations in length. From these trials values for both the %Blocking and %Waiting arising at each workstation along the line were obtained. This information was then used to develop models capable of estimating the levels of %Blocking and %Waiting arising at individual workstations.

Trials 4: Here a series of trials were designed with the aim of identifying the effects of mixed levels of workstation variability within a flow line, i.e.:

i. Two-workstation lines were tested in which each workstation possessed different levels of variability as shown in Figure 4.12. All combinations of pairs of the 15 categories i.e. 225 models were examined.

ii. Flow lines of 5, 7 and 9 workstations in length were simulated in which one workstation within each line possessed a different level of variability to the remaining workstations within the line. Trials were carried out with the workstation possessing the different level of variability positioned at the start, middle and end of the flow line.

iii. Flow lines of 5 workstations in length were simulated in which ***one*** workstation within each line possessed a different level of variability to the remaining workstations within the line. The trials carried out involved placing this workstation at differing positions along the line.

iv. Flow lines of 5 workstations in length were simulated in which ***two*** workstations within each line possessed a different level of variability to the remaining workstations within the line. The trials carried out involved placing these two workstations at differing positions along the line.

v. Flow lines of 5 workstations in length were simulated in which ***three*** workstations within each line possessed a different level of variability to the remaining workstations within the line. The trials carried out involved placing these three workstations at differing positions along the line.

vi. Flow lines of 21 workstations in length were simulated in which the variability of each workstation was selected with care to include a wide variety of variability levels between workstations and sudden large changes in variability levels between adjacent workstations.

Chapter 5 Experimental Results

5.1 Introduction

In Chapter 4 a methodology was developed for combining the variability probability distributions associated with the individual tasks within a workstation into a single variability probability distribution for a workstation. Details were provided of the experimental tests undertaken to validate the individual steps involved in this methodology. This chapter presents the results and brief observations of these tests.

In addition, simulation experiments were carried out, using these single workstation variability probability distributions to determine the effect of this variation on the utilisation of individual workstations within a flow line. This chapter also presents the results and brief observations of these experiments and provides equations developed for estimating levels of blocking and waiting on individual workstations within a flow line.

More detailed analysis of results is provided in Chapter 6 Discussion.

5.2 Main Task 1: Results and Observations

Test 1: Results from the simulation models constructed to test the validity of employing the extension to Hopp's availability equation to determine the values shown in Figure 4.6 are provided in Table 5.1. Within this table the values using Equations 7, 8 and 9 have been compared with actual results obtained from simulation models.

TAKT	Short Stoppages						Availability						Mean Percentage Error		
	Time between occurrences			Duration			Results from Equations [7] [8] [9]			Results from Simulation Models					
Time	a	t	b	a	t	b	a_{SSA}	t_{SSA}	b_{SSA}	a_{SSA}	t_{SSA}	b_{SSA}	a_{SSA}	t_{SSA}	b_{SSA}
1	10	30	60	1	2	3	0.77	0.94	0.98	0.75	0.91	0.96	-2.56%	-3.02%	-2.46%
1	10	30	60	2	5	6	0.63	0.86	0.97	0.61	0.85	0.94	-2.46%	-0.84%	-2.95%
1	10	30	60	3	4	6	0.63	0.88	0.95	0.62	0.86	0.93	-0.81%	-2.60%	-2.41%
1	10	30	60	1	3	6	0.63	0.91	0.98	0.62	0.90	0.97	-0.81%	-1.01%	-1.40%
1	10	30	60	3	4	5	0.67	0.88	0.95	0.65	0.86	0.93	-2.56%	-2.60%	-2.41%
1	10	20	30	2	5	6	0.63	0.80	0.94	0.62	0.83	0.91	-0.81%	3.61%	-3.02%
1	5	10	15	3	4	6	0.45	0.71	0.83	0.43	0.69	0.81	-5.71%	-3.52%	-2.88%
1	10	20	30	1	2	3	0.77	0.91	0.97	0.75	0.89	0.96	-2.56%	-2.15%	-0.81%
1	15	30	45	1	3	6	0.71	0.91	0.98	0.69	0.89	0.97	-3.52%	-2.15%	-0.85%
10	10	30	60	1	2	3	0.77	0.94	0.98	0.74	0.92	0.95	-3.95%	-1.90%	-3.54%
10	10	30	60	2	5	6	0.63	0.86	0.97	0.61	0.89	0.95	-2.46%	3.69%	-1.87%
100	10	30	60	1	2	3	0.77	0.94	0.98	0.74	0.92	0.97	-3.95%	-1.90%	-1.40%
100	10	30	60	2	5	6	0.63	0.86	0.97	0.62	0.84	0.95	-0.81%	-2.04%	-1.87%

Table 5.1: Mean % Error arising from use of Short Stoppage Availability Equations 7, 8 and 9

From these results the following observations can be made, i.e.:

1. Values for a_{SSA}, b_{SSA} and t_{SSA} obtained from Equations 7, 8 and 9 are in close agreement with those results obtained from simulation models, i.e. Mean Percentage Errors range between and -5.71% and +3.69%.
2. There appears to be no close relationships between the levels of error produced and Short Stoppage Time between Occurrences or Short Stoppage Durations, i.e. correlation coefficients range from -0.01 to 0.58.

Test 2: Results from the simulation models constructed to test the validity of employing the extension to Hopp and Spearman's (1996) availability equation to determine the values shown in Figure 4.7 are provided in Table 5.2. Within this table the values using Equations 10, 11 and 12 have been compared with actual results obtained from these simulation models.

TAKT Time	Long Stoppages: Time between occurrences			Long Stoppages: Duration			Results from Availability Equations [10]	[11]	[12]	Results from Simulation Models			Mean Percentage Error		
	a	t	b	a	t	b	a_{LSA}	t_{LSA}	b_{LSA}	a_{LSA}	t_{LSA}	b_{LSA}	a_{LSA}	t_{LSA}	b_{LSA}
1	20	40	80	10	20	30	0.40	0.67	0.89	0.39	0.65	0.85	-2.56%	-2.56%	-4.58%
1	20	40	80	10	40	50	0.29	0.50	0.89	0.27	0.47	0.83	-5.82%	-6.38%	-7.10%
1	20	40	80	10	40	60	0.25	0.50	0.89	0.24	0.48	0.82	-4.17%	-4.17%	-8.40%
1	20	40	80	20	30	50	0.29	0.57	0.80	0.28	0.55	0.78	-2.04%	-3.90%	-2.56%
1	20	40	80	20	30	40	0.33	0.57	0.80	0.31	0.56	0.78	-7.53%	-2.04%	-2.56%
1	20	40	80	30	40	50	0.29	0.50	0.73	0.27	0.48	0.71	-5.82%	-4.17%	-2.43%
1	20	40	80	30	50	60	0.25	0.44	0.73	0.23	0.42	0.69	-8.70%	-5.82%	-5.40%

Table 5.2: Mean % Error arising from use of Long Stoppage Availability Equations 10, 11 and 12

From these results the following observations can be made, i.e.:

1. Values for a_{LSA}, b_{LSA} and t_{LSA} obtained from Equations 10, 11 and 12 are in close agreement, if slightly biased in the negative direction, with those results obtained from simulation models, i.e. Mean Percentage Errors range between -2.04% to -8.70%.

2. There appears to be no close relationships between the levels of error produced and Long Stoppage Time between Occurrences or Long Stoppage Durations, i.e. correlation coefficients range from -0.17 to 0.62.

Test 3: Results from the simulation models constructed to test the validity of employing Equations 13, 14 and 15 to determine effective task times are shown in Table 5.3. Within this table the values using Equations 13, 14 and 15 have been compared with actual results obtained from these simulation models.

Task Cycle Times			Results from Short Stoppage Availability Equations			Total Effective Cycle Time						Mean Percentage Error		
						Results from Equations [13]	[14]	[15]	Results from Simulation Models					
a	t	b	a_{SSA}	t_{SSA}	b_{SSA}	a_{ECT_SS}	t_{ECT_SS}	b_{ECT_SS}	a_{ECT_SS}	t_{ECT_SS}	b_{ECT_SS}	a_{ECT_SS}	t_{ECT_SS}	b_{ECT_SS}
1	3	5	0.77	0.94	0.98	1.02	3.30	6.67	0.99	3.26	6.67	-2.69%	-1.13%	0.05%
1	3	6	0.63	0.86	0.97	1.03	3.53	9.84	1.00	3.46	9.90	-3.33%	-2.01%	0.65%
1	3	4	0.63	0.88	0.95	1.05	3.49	6.45	1.02	3.47	6.33	-2.94%	-0.53%	-1.92%
2	3	5	0.63	0.91	0.98	2.03	3.33	8.06	1.98	3.30	7.96	-2.69%	-1.01%	-1.31%
2	3	6	0.67	0.88	0.95	2.10	3.49	9.23	2.06	3.44	9.15	-1.94%	-1.41%	-0.88%
1	3	5	0.77	0.94	0.98	1.07	3.61	8.06	1.05	3.51	7.99	-1.59%	-2.98%	-0.93%
1	3	6	0.63	0.8	0.9	1.20	4.35	13.95	1.18	4.29	13.80	-1.69%	-1.35%	-1.11%
1	3	4	0.45	0.71	0.83	1.03	3.37	5.33	1.07	3.42	5.38	3.43%	1.44%	0.87%
2	3	5	0.71	0.91	0.98	2.04	3.37	7.25	2.01	3.33	7.15	-1.71%	-1.22%	-1.35%
1	3	5	0.77	0.94	0.98	1.02	3.26	6.76	1.02	3.27	6.74	0.33%	0.28%	-0.25%
1	3	6	0.63	0.86	0.97	1.03	3.37	9.84	1.01	3.34	9.82	-2.31%	-0.92%	-0.16%
1	3	5	0.77	0.94	0.98	1.02	3.26	6.76	1.01	3.23	6.71	-0.66%	-0.96%	-0.70%
1	3	6	0.63	0.86	0.97	1.03	3.57	9.68	1.00	3.54	9.61	-3.33%	-0.89%	-0.70%

Table 5.3: Mean % Error arising from use of Effective Cycle Time Equations 13, 14 and 15

From these results the following observations can be made, i.e.:

1. Values for a_{ECT_SS}, b_{ECT_SS} and t_{ECT_SS} obtained from Equations 13, 14 and 15 are in close agreement with those results obtained from simulation models, i.e. Mean Percentage Errors range between -3.33% to + 3.43%.
2. There appears to be no close relationships between the levels of error produced and availabilities or Task Cycle Times, i.e. correlation coefficients range from -0.01 to 0.61.

Test 4: Results from the simulation models constructed to test the validity of employing Equations 16, 17 and 18 to determine effective task times are shown in Table 5.4. Within this table the values using Equations 16, 17 and 18 have been compared with actual results obtained from the simulation models.

Results from Long Stoppage Availability Equations			Total Effective Cycle Time						Mean Percentage Error		
			Results from Equations			Results from Simulation Models					
			[16]	[17]	[18]						
a_{LSA}	t_{LSA}	b_{LSA}	$a_{ECT\_SS\&LS}$	$t_{ECT\_SS\&LS}$	$b_{ECT\_SS\&LS}$	$a_{ECT\_SS\&LS}$	$t_{ECT\_SS\&LS}$	$b_{ECT\_SS\&LS}$	$a_{ECT\_SS\&LS}$	$t_{ECT\_SS\&LS}$	$b_{ECT\_SS\&LS}$
1.20	5.07	7.84	1.02	3.30	6.67	1.17	4.98	7.76	-2.23%	-1.84%	-1.07%
1.24	7.51	11.85	1.03	3.53	9.84	1.28	7.58	11.92	2.74%	0.93%	0.58%
1.28	7.27	7.87	1.05	3.49	6.45	1.25	7.18	7.77	-2.44%	-1.22%	-1.26%
2.61	6.06	10.34	2.03	3.33	8.06	2.55	5.98	10.15	-2.23%	-1.35%	-1.86%
2.69	6.23	11.83	2.10	3.49	9.23	2.58	6.18	11.75	-4.35%	-0.80%	-0.72%

Table 5.4: Mean % Error Arising from Use of Effective Cycle Time Equations 16, 17 and 18

From these results the following observations can be made, i.e.:

1. Values for $a_{ECT\_SS\&LS}$, $b_{ECT\_SS\&LS}$, $t_{ECT\_SS\&LS}$ obtained from Equations 16, 17 and 18 are in close agreement with those results obtained from simulation models, i.e. Mean Percentage Errors range between -4.35% to +2.74%.

2. There appears to be no close relationships between the levels of error produced and the total effective cycle times or the cycle times, i.e. correlation coefficients range from -0.58 to 0.46.

Test 5: Results from the simulation models constructed to test the validity of employing Equations 19, 20 and 21 to combine individual task variabilities into a single variability probability distribution for a workstation are shown in Table 5.5. Within this table simulation results for $a_{ECT\_SS\&LS}$, $b_{ECT\_SS\&LS}$ and $t_{ECT\_SS\&LS}$ have been compared with values calculated from Task Cycle Times using equations 19, 20 and 21.

Work Station Number	Task Number	Task Cycle Times			Expected Value (a+4t+b/6)	Results from Simulation Models	Mean % Error
		$a_{ECT\_SS\&LS}$	$t_{ECT\_SS\&LS}$	$b_{ECT\_SS\&LS}$			
1	1	1	3	4	2.83	2.7	-0.13
	2	2	3	5	3.17	3.06	-0.10
	3	2	3	6	3.33	3.29	-0.05
Workstation 1 Total =		**5**	**9**	**15**	**9.33**	**9.25**	**-0.90**

Work Station Number	Task Number	Task Cycle Times			Expected Value (a+4t+b/6)	Results from Simulation Models	Mean % Error
		$a_{ECT\_SS\&LS}$	$t_{ECT\_SS\&LS}$	$b_{ECT\_SS\&LS}$			
2	1	2	3	4	3.00	3.00	0.00
	2	1	3	5	3.00	3.00	0.00
	3	1	3	6	3.17	3.06	0.11
	4	0	3	4	2.67	2.32	-0.35
	5	0	3	5	2.83	2.69	-0.14
	6	0	3	6	3.00	3.01	0.01
Workstation 2 Total =		**4**	**18**	**30**	**17.67**	**17.62**	**-0.26**

Table 5.5: Mean %Error arising from the use of PERT Equations 19, 20 and 21

From these results the following observations can be made, i.e.:

1. For both workstations the Effective Cycle Time values calculated using Equations 19, 20 and 21 and the total Effective Cycle Time for complete flow lines are in close agreement with those obtained from simulation models, i.e. Mean Percentage Errors range between -0.35% to +0.11%.

2. There appears to be no close relationships between the levels of error produced and Effective Cycle Times, i.e. correlation coefficients range from -0.14 to -0.45.

5.3 Main Task 2: Results and Observations

Trials 1: These trials used visual examination of the outputs from simulation models to identify the basic manner in which %Blocking and %Waiting of individual workstations varied along a flow line, i.e.:

i. From the flow lines in which each workstation exhibited the same level of variability the results for variability distributions *a=3:t=3:b=4* and *a=0:t=3;b=6* are presented. For each of these workstation distributions the results for the flow lines of 2, 3, 5, 8, 13 and 21 workstations in length are shown in Figures 5.1 and 5.2. Results from all other variability distributions examined indicated similar patterns of %Blocking and %Waiting and are provided in Appendix 1. This Appendix contains all the basic simulation results for all Figures and Tables provided in Sections 5.3.

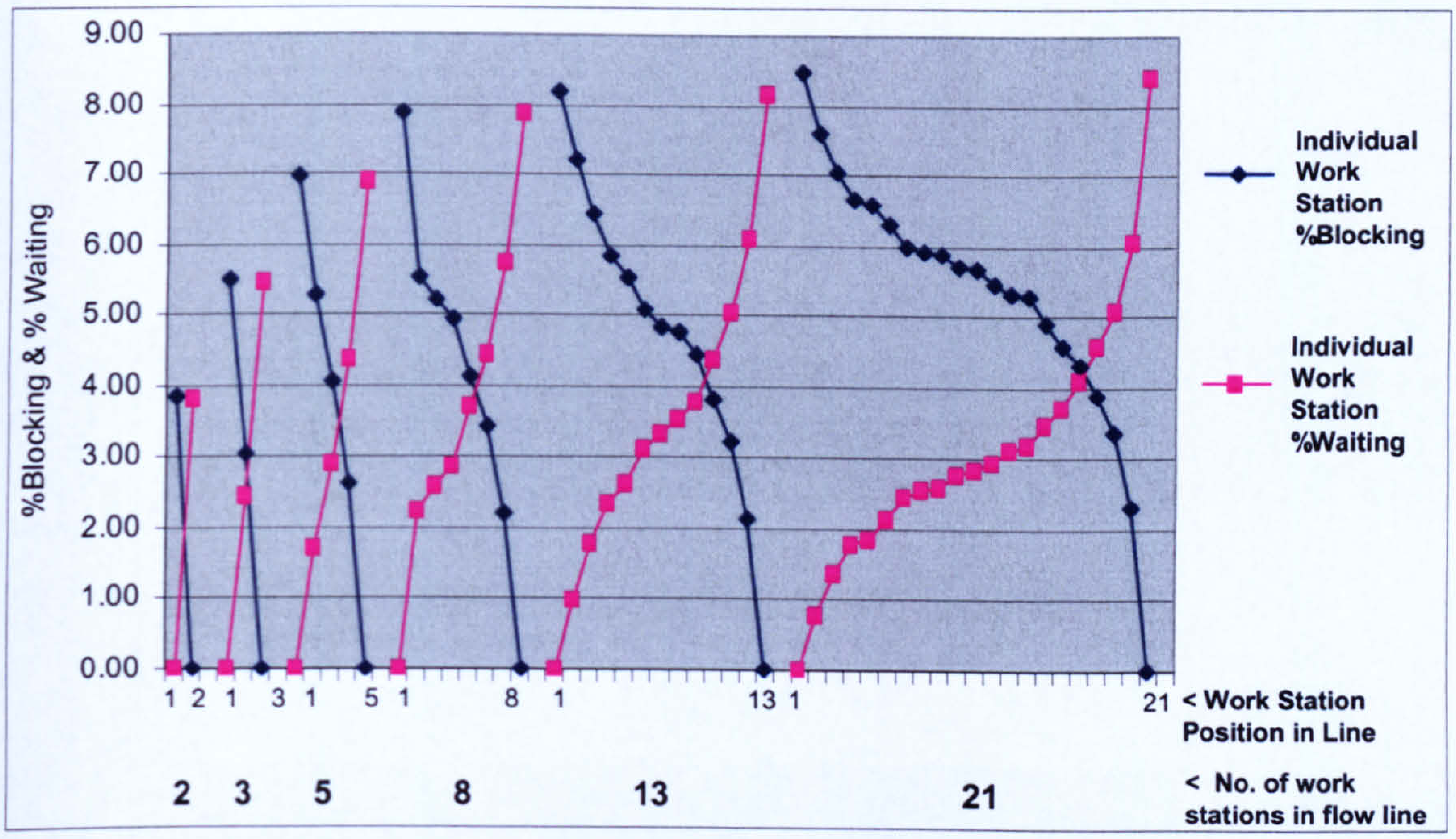

Figure 5.1: %Blocking & %Waiting on 2, 3, 5, 8, 13 and 21 Workstation Flow Lines: 334 Variability (see Fig. 4.12): All results derived from Simulation Models

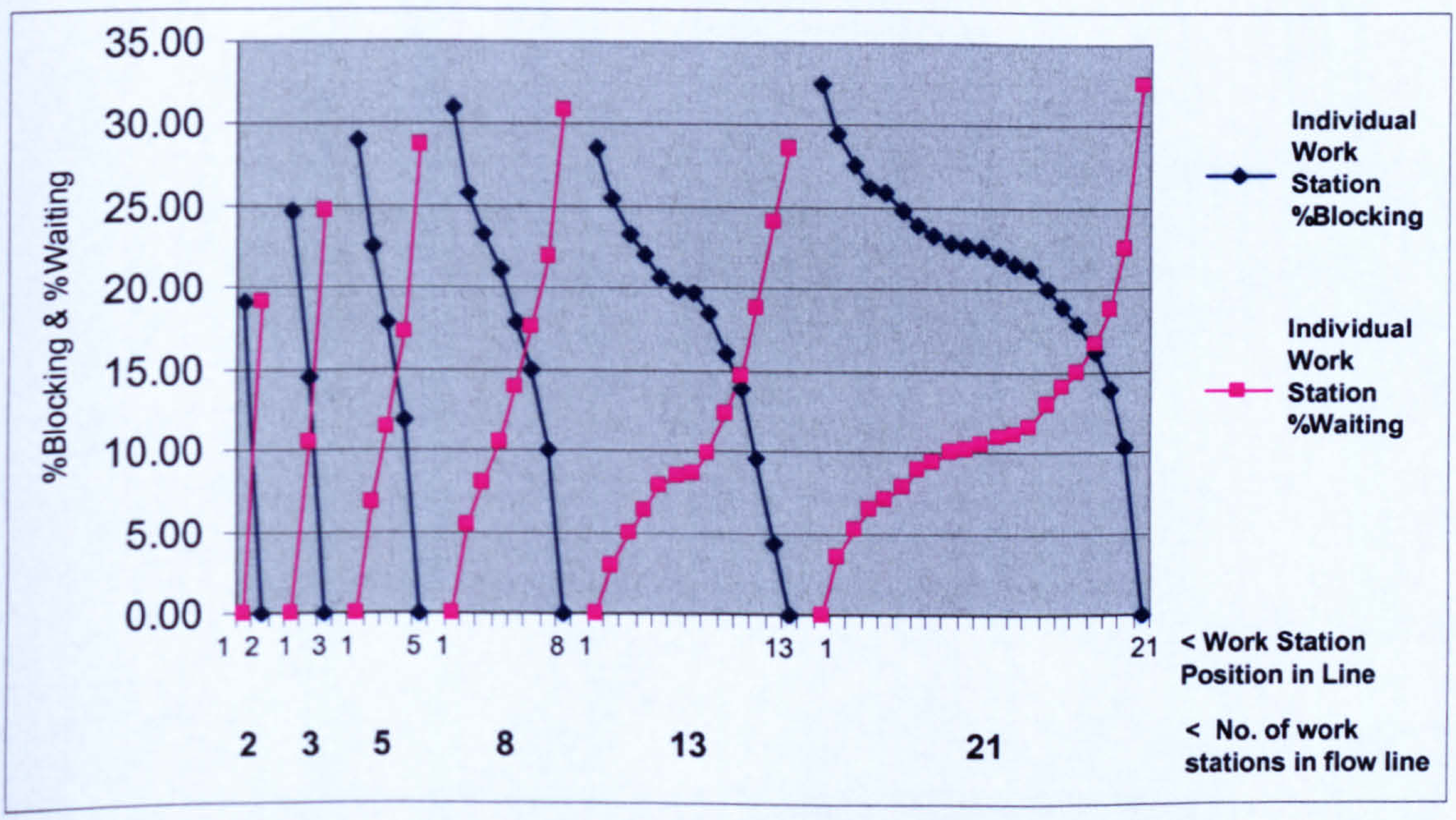

Figure 5.2: %Blocking & %Waiting on 2, 3, 5, 8, 13 and 21 Workstation Flow Lines: 036 Variability (see Fig. 4.12): All results derived from Simulation Models

The results shown in Figures 5.2 and 5.3 indicated that the following basic rules held at all levels of workstation variability, i.e.:

a. The %Blocking at the 1st workstation was approximately equal to the %Waiting at the last workstation in the line.
b. The value of the maximum level of %Blocking, and hence %Waiting, is related both to the level of variability exhibited by workstations and the number of workstations within the flow line.
c. The %Blocking was at its maximum at the 1st workstation and gradually decreased at each subsequent workstation until becoming zero at the last workstation. It is assumed that items can always exit instantaneously from the last workstation and hence no blocking occurs at this work area.
d. The %Waiting was zero at the 1st workstation and gradually increased at each subsequent workstation until reaching its maximum at the last workstation. It is assumed there is no waiting for items to be transferred to the 1st workstation, i.e. instantaneous replenishment.
e. The sum of the %Blocking and %Waiting were approximately equal at all workstations along the line.
f. The relationships between %Blocking and %Waiting along the flow line, i.e. follows the "mirroring effect" identified by Payne et. al. (1972) as illustrated in Figure 5.13 using a 10 workstation flow line.

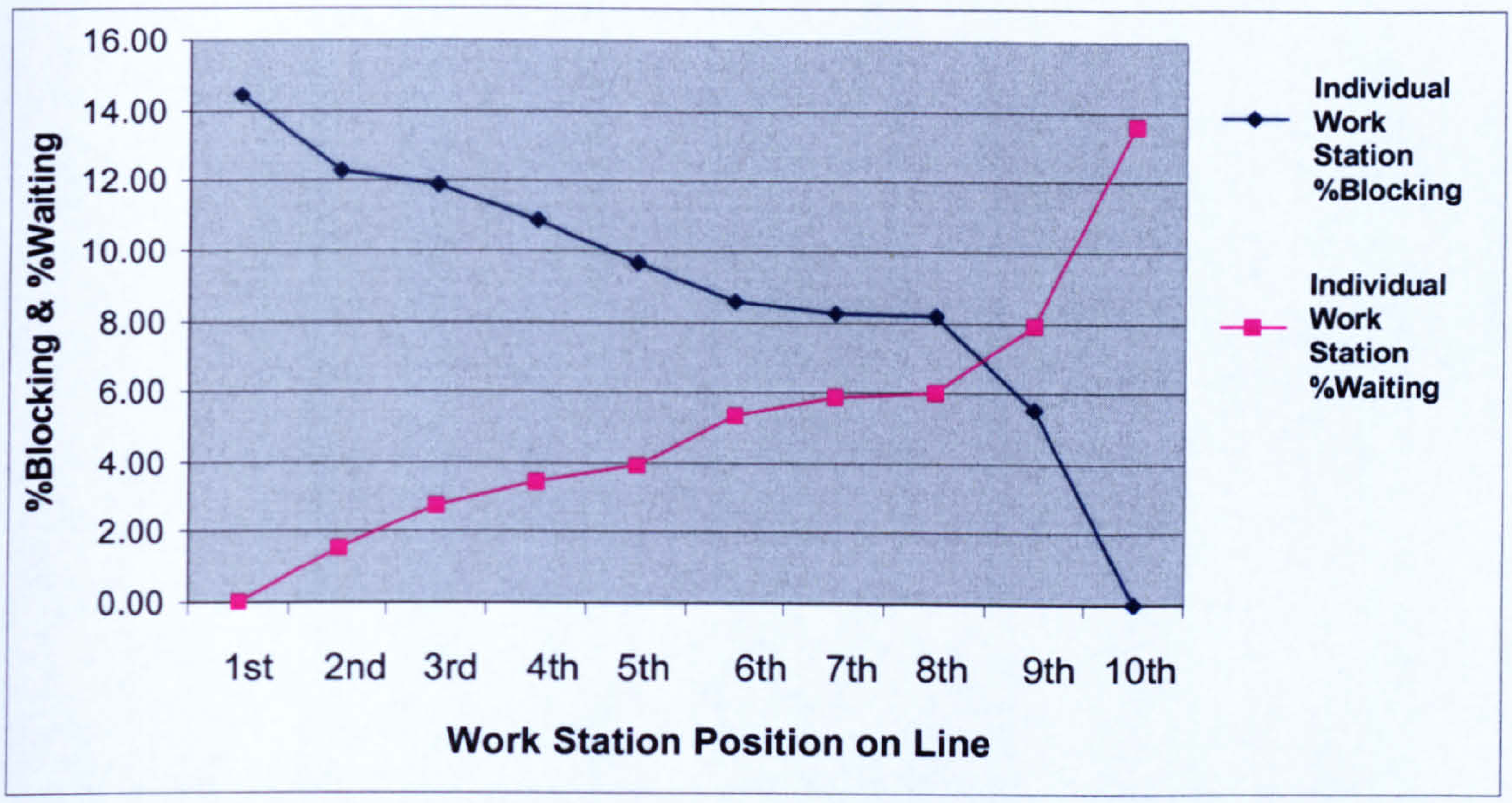

Figure 5.3: %Blocking & %Waiting on a 10 Workstation Flow Line: Common Workstation Variability: All results derived from Simulation Models

ii. From the flow lines in which one or more workstations exhibited differing levels of variability the results using two variability distributions, *a=0:t=3:b=6* and *a=0:t=3:b=3*, are presented in Figure 5.4. Flow lines of 2, 5, 7 and 9 workstations in length were examined. In the case of the 5, 7 and 9 workstation lengths the workstations exhibiting the differing levels of variability occupied the 2nd workstation position.

Results from other distributions examined indicated that no common pattern of %Blocking and %Waiting existed. The results, however, did indicate that at the workstations preceding and succeeding the workstation with differing variability the relative amounts of %Blocking and %Waiting were disturbed. The probable causes influencing the relative amounts of disturbance could not be visually identified although line length did not appear to have a significant affect on these values.

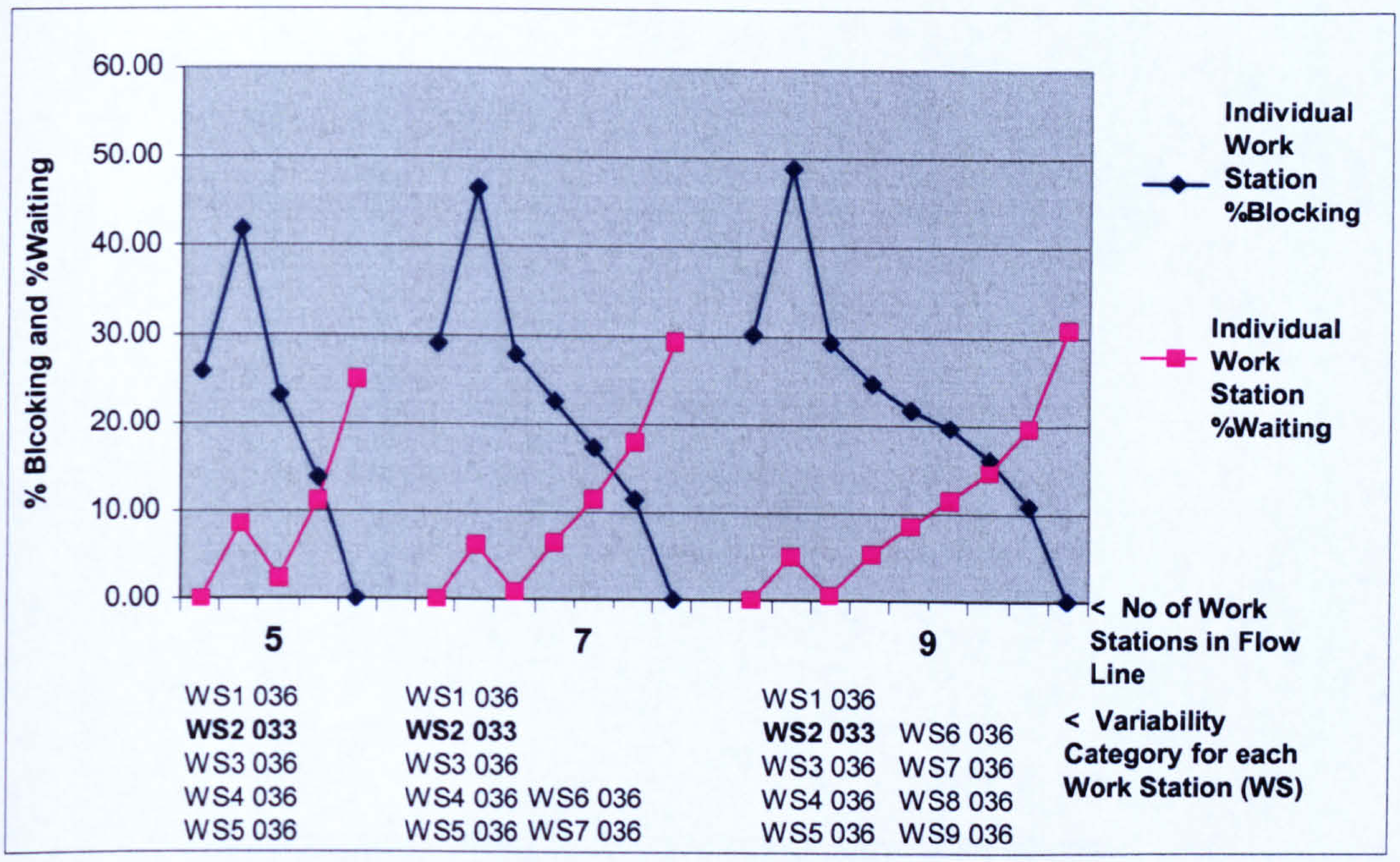

Figure 5.4 %Blocking and %Waiting on 5, 7 and 9 Workstation Flow Lines: Mixed Workstation (WS) Variability: All results derived from Simulation Models

Trials 2: These trials were designed to *quantify* the effect of individual levels of variability on workstation blocking and waiting. For each of the 15 variability categories shown in Figure 4.12 two-workstation flow lines were simulated in which each workstation possessed the same level of variability. Correlation coefficients were used to compare the workstation %Blocking and %Waiting levels arising from simulation models with variability means, geometric means, harmonic means, PERT means, standard deviations, coefficient of variations and the medians of the workstation cycle time variabilities. Correlation coefficient results are listed in Table 5.6 and comparisons of each statistical measure with %Blocking and %Waiting illustrated in Figure 5.5.

Statistical Measure	% Blocking	% Waiting
Mean	-0.39	-0.42
Geometric Mean	-0.80	-0.82
Harmonic Mean	-0.86	-0.87
PERT Mean	-0.39	-0.42
Median	0.05	0.03
Standard Deviation	0.91	0.90
Coefficient of Variation	1.00	1.00

Table 5.6 Correlation Coefficient Values for Statistical measures with %Blocking & %Waiting on 2 Workstation Flow Lines

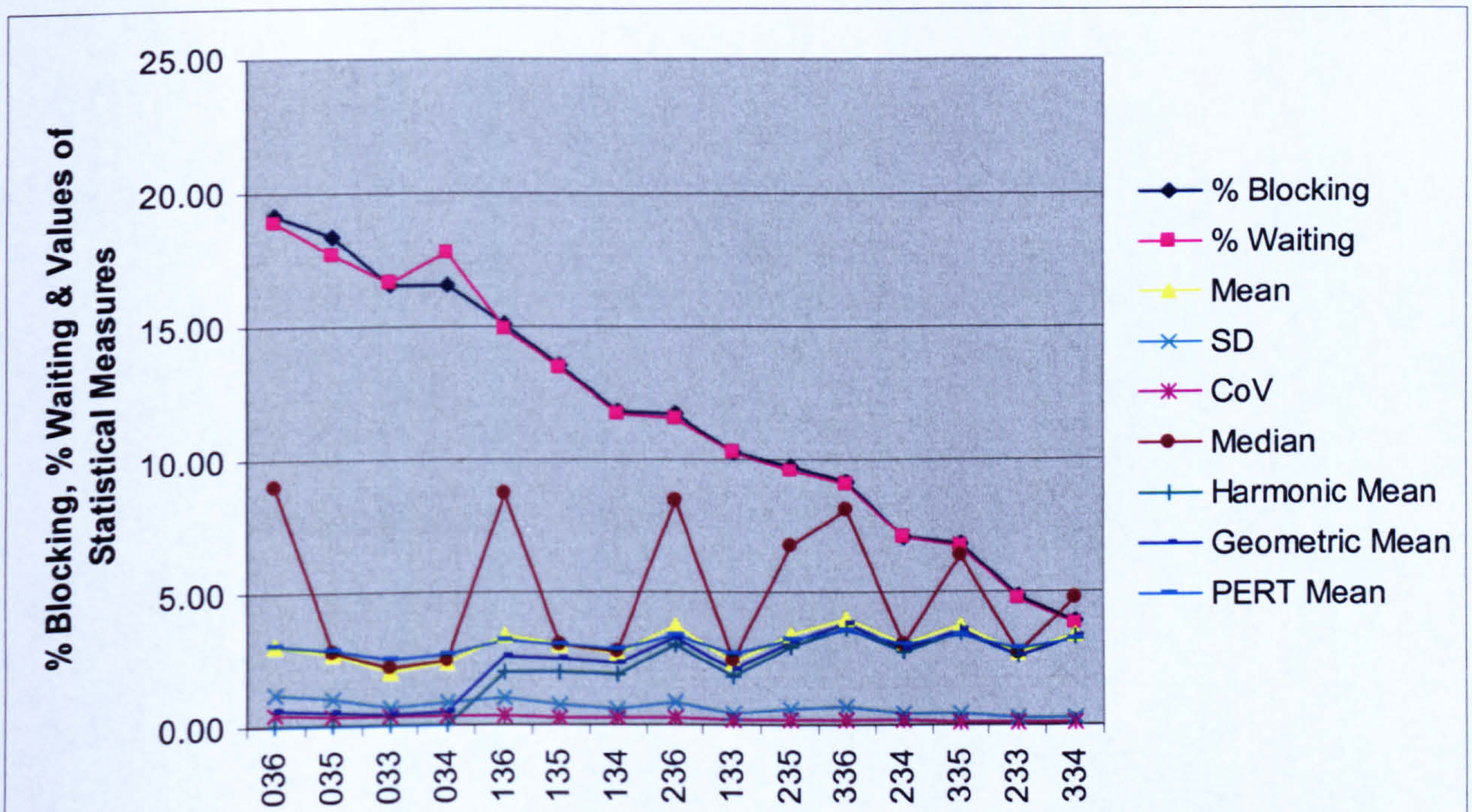

Figure 5.5: Correlation Coefficient Values for 7 Statistical Measures with %Blocking & %Waiting on 2 Workstation Flow Lines

It can be seen that of the statistical measures listed in Table 5.5 the *coefficient of variation* possesses the greatest level of correlation. The data provided by the simulation results were then used to develop estimating equations for using the *coefficient of variation* to calculate %Blocking and %Waiting arising from a specific variability category. Models were developed using the Genehunter GA package (Lewinson, 1995) to analyse the data and determine relationships that minimised errors. Equations 22 and 23were identified:

$$\%B_{1,2} = 1.37 + (40.33.CV_{1,2}) \tag{22}$$

Where:

$\%B_{1,2}$ = %Blocking on the 1st Workstation of a 2-workstation flow line.
$CV_{1,2}$ = Coefficient of variation of the 1st Workstation of a 2-workstation flow line.

Here the first subscript of the notation (e.g. $\%B_{1,2}$) identifies the position of the workstation along the flow line and the second subscript identifies the number of workstations in the flow line.

Since the equation is calculating a percentage value the maximum positive and negative differences between simulation and estimated values were used to determine estimating accuracy, i.e. differences ranged between -0.51 and +0.53.

$$\%\,W_{2,2} = 0.98 + (44.51\,.\,CV_{1,2}) \tag{23}$$

Where:

$\%W_{2,2}$ = %Waiting on the 2[nd] Workstation of a 2-workstation flow line

Again maximum positive and negative differences between simulation and estimated values were used to determine estimating accuracy, i.e. these differences ranged between -0.46 and +0.38.

Figure 5.6 illustrates the close agreement achieved between estimated and simulation values for both blocking and waiting estimating models.

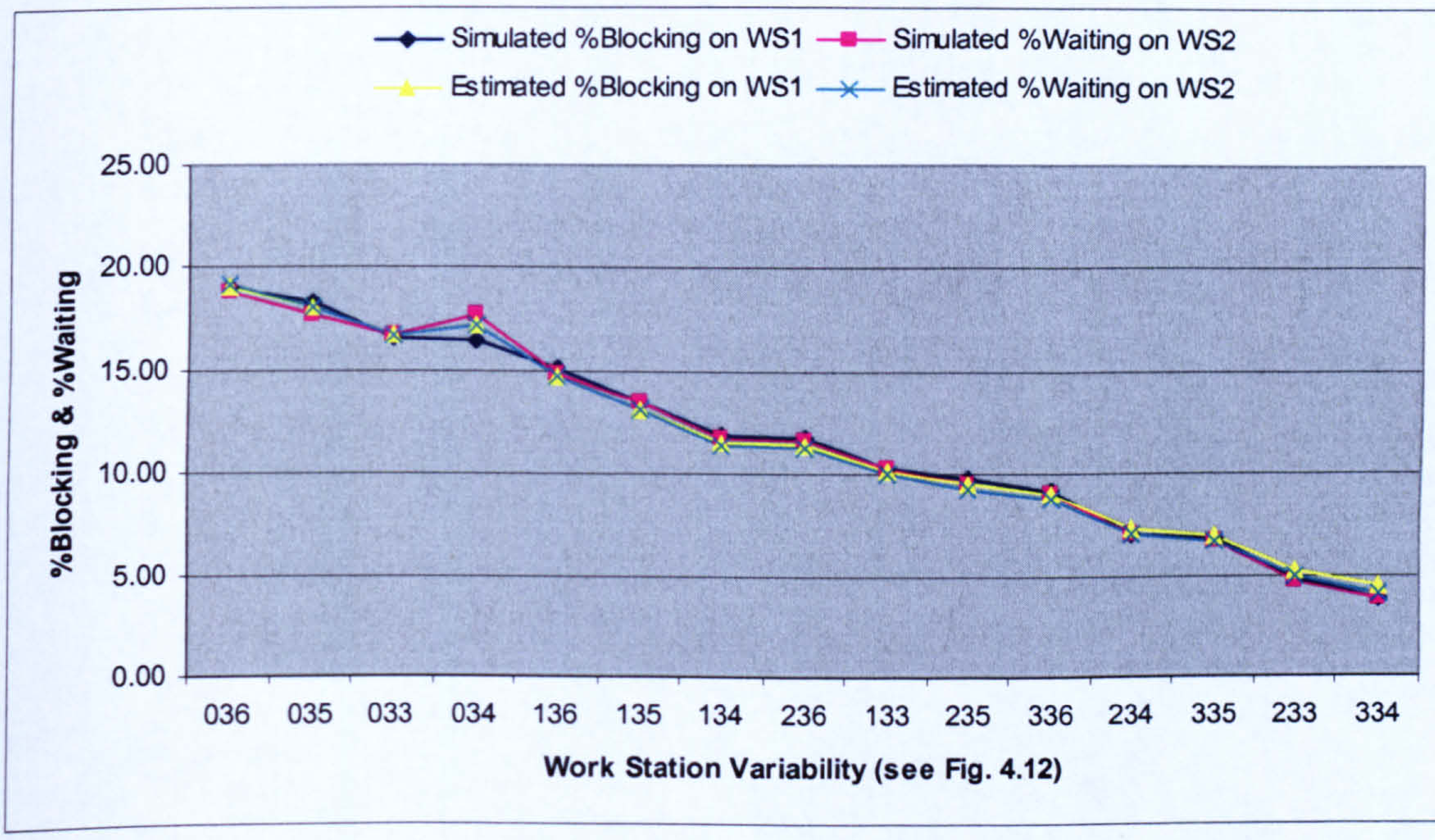

Figure 5.6: Comparison of Estimated vs. Simulated %Blocking & %Waiting on 2 Workstation (WS) Flow Lines: Estimated Values derived from Equations 22 & 23: Simulated Values derived from Simulation Models

Trials 3: These trials were intended to identify the relationships between %Blocking and %Waiting and both the 'number of workstations within a flow line' and the 'position of an individual workstation along the line'. Here trials involved simulating flow lines of varying length for each of the variability categories shown in Figure 4.12. Flow lines examined all exhibited common levels of variability at each workstation along the line and were of 2, 3, 5, 8, 13 and 21 workstations in length. Results from these simulation trials are shown in Figures 5.7 to 5.13. From these trials values for both the %Blocking and %Waiting arising at each workstation along the line were obtained.

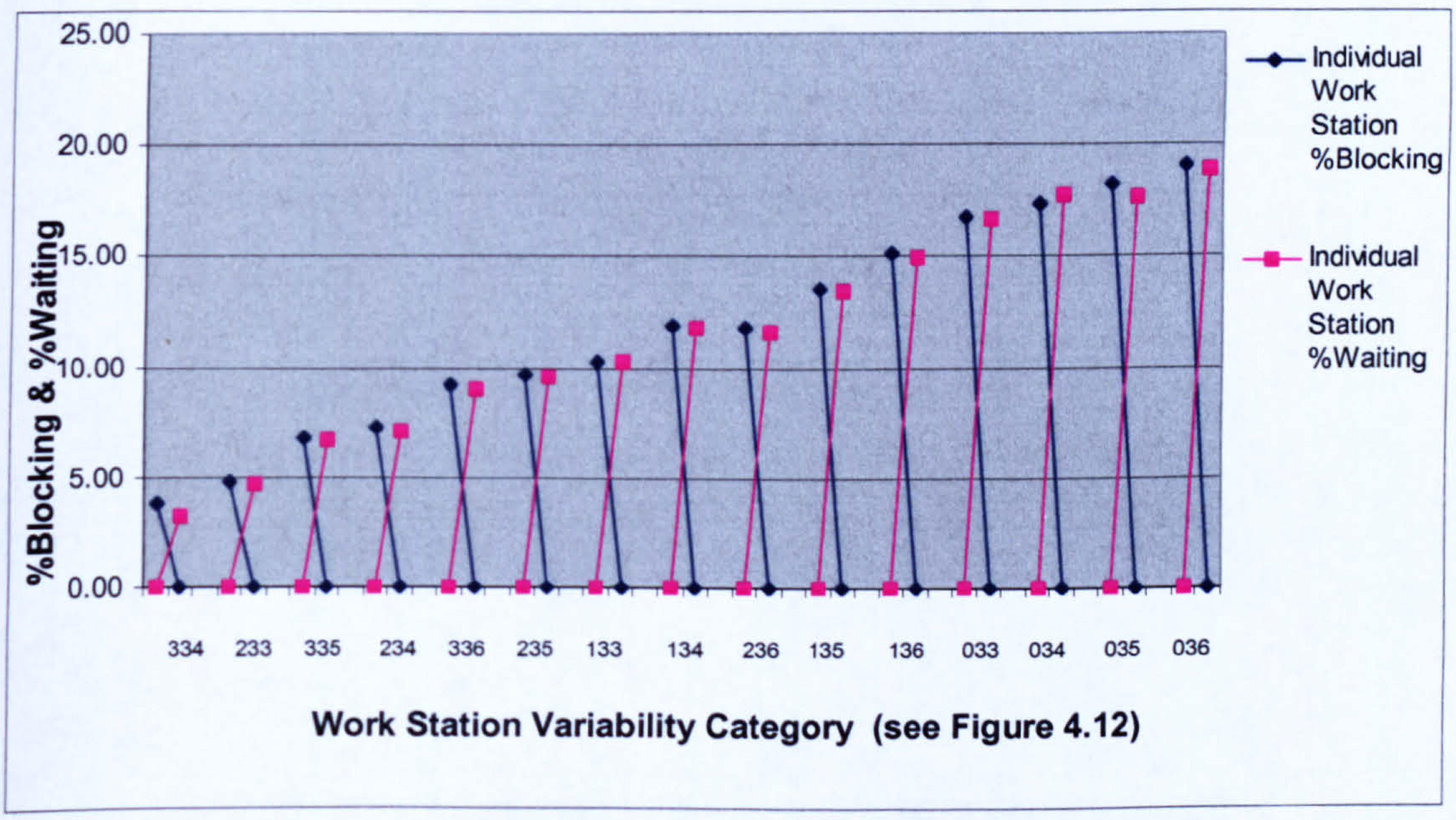

Figure 5.7: % Blocking and %Waiting on 2 Workstation Flow Lines: All results derived from Simulation Models

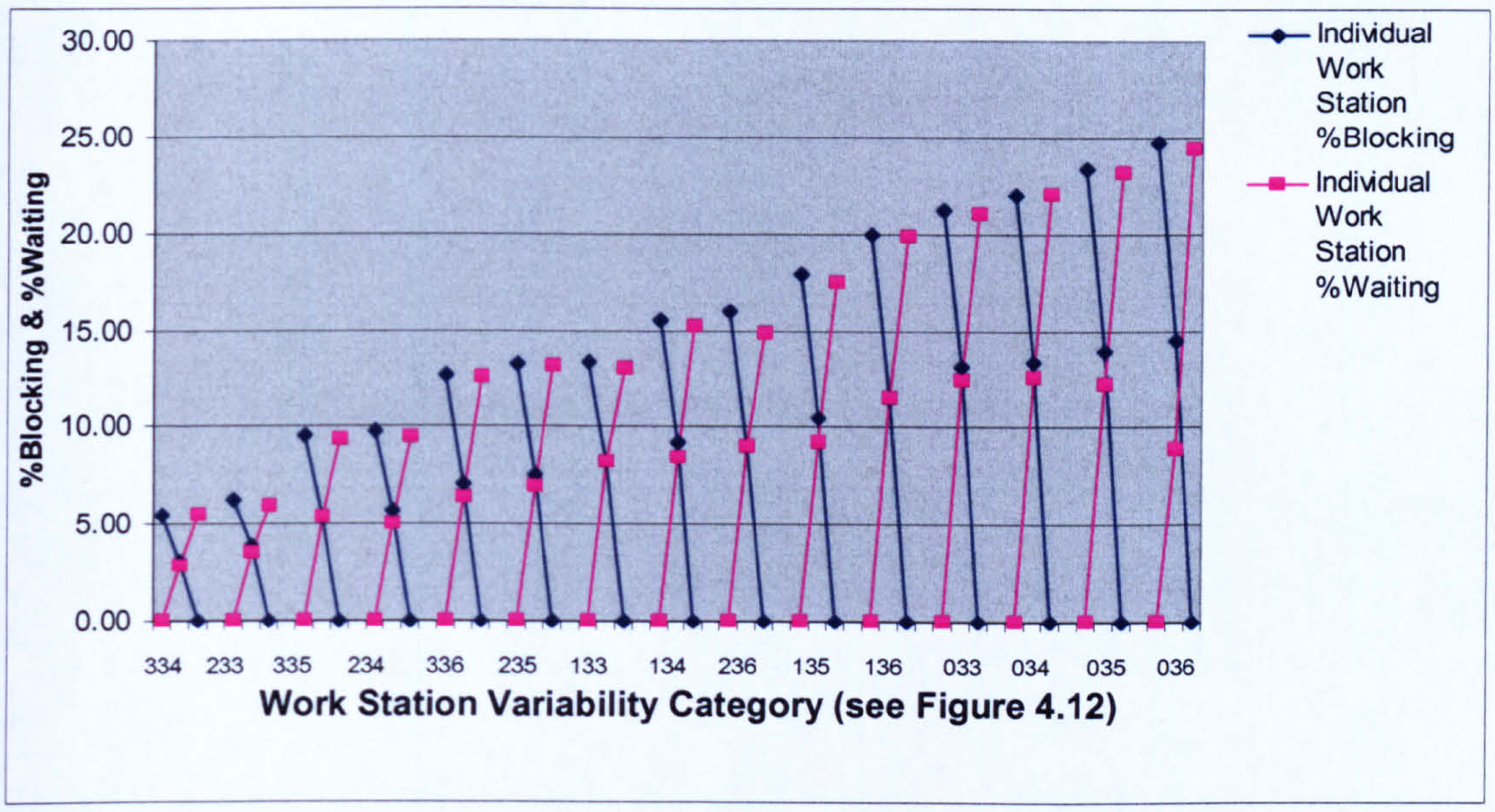

Figure 5.8: % Blocking and %Waiting on 3 Workstation Flow Lines: All results derived from Simulation Models

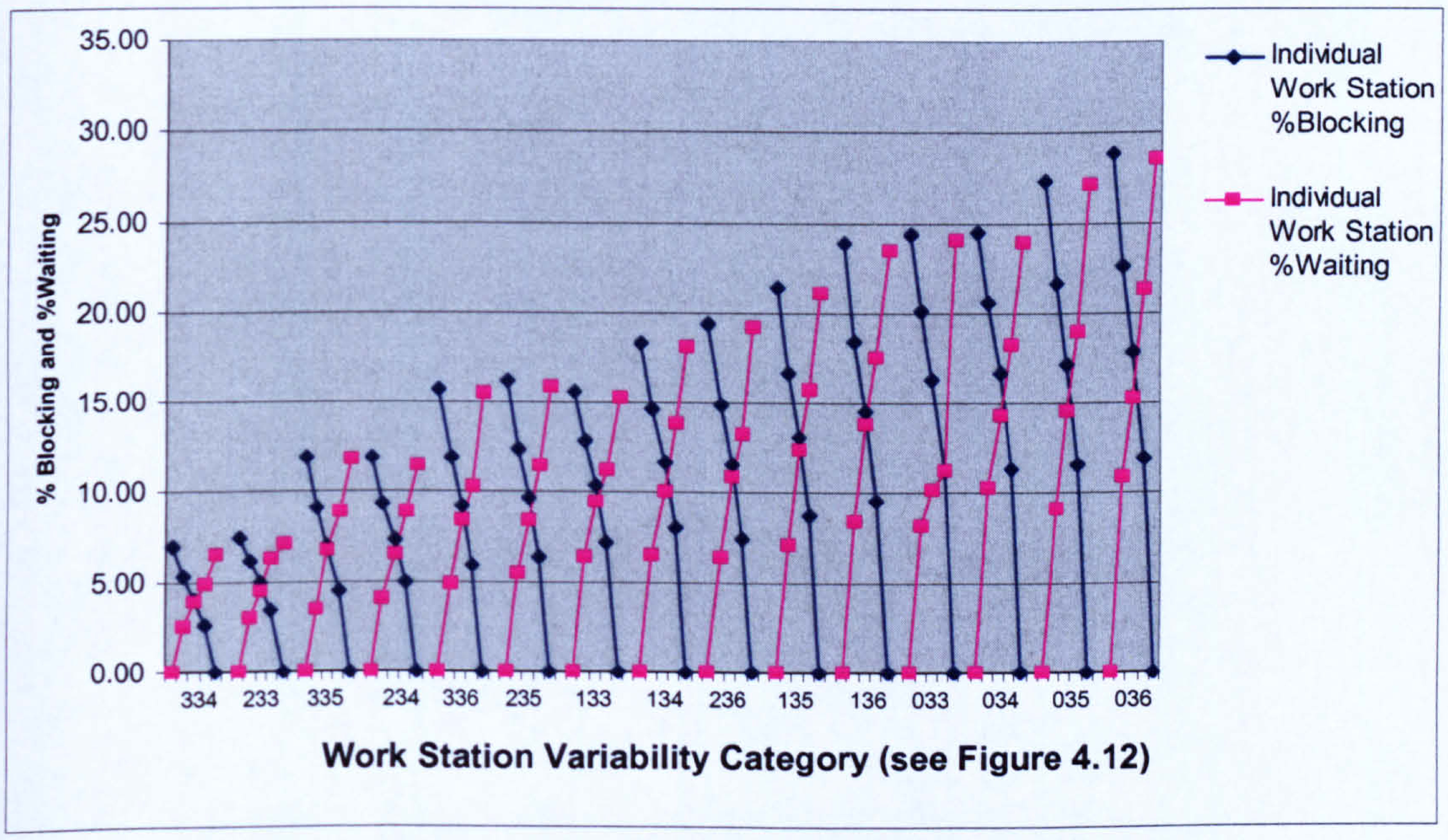

Figure 5.9: % Blocking and %Waiting on 5 Workstation Flow Lines: All results derived from Simulation Models

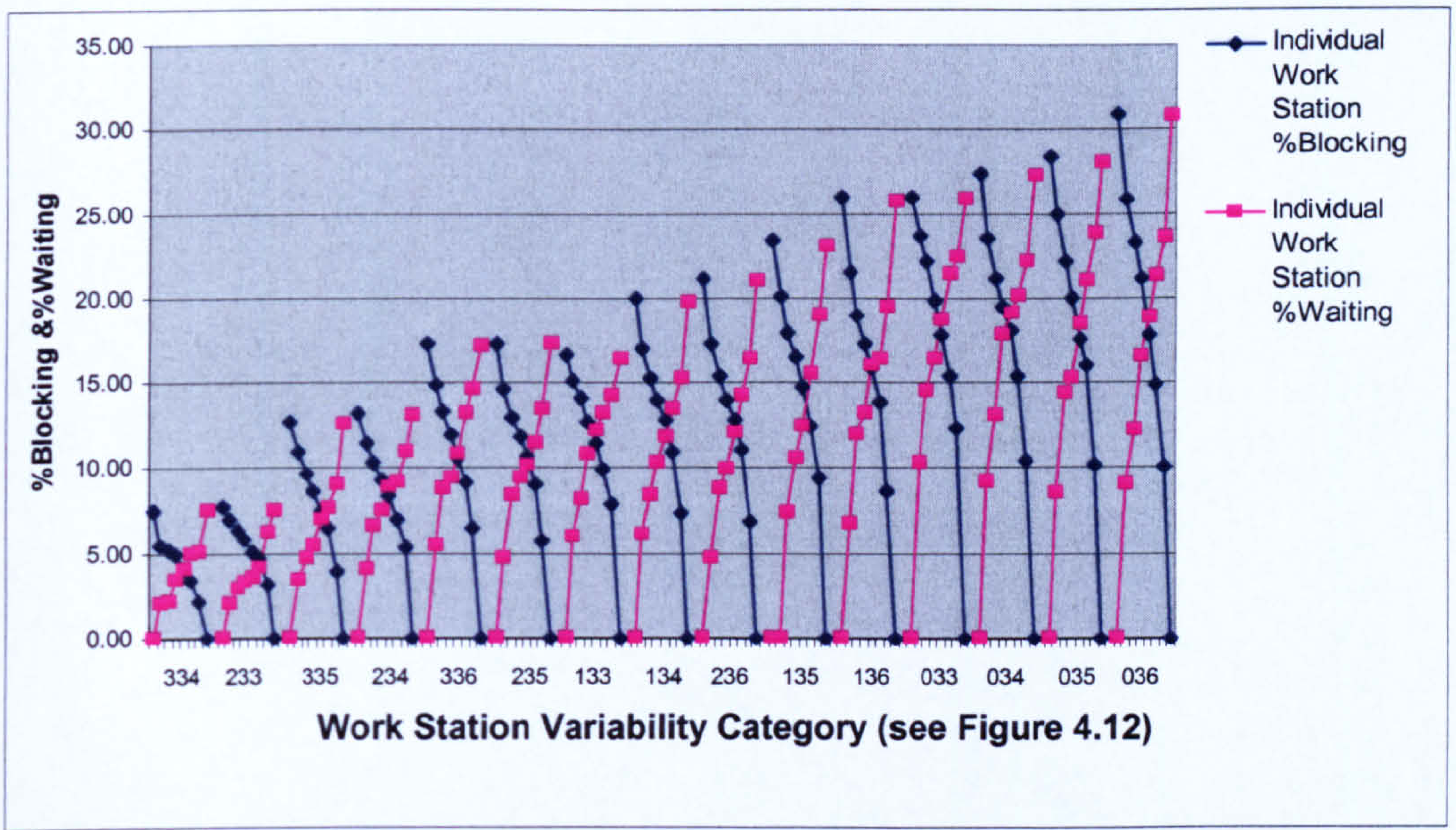

Figure 5.10: % Blocking and %Waiting on 8 Workstation Flow Lines: All results derived from Simulation Models

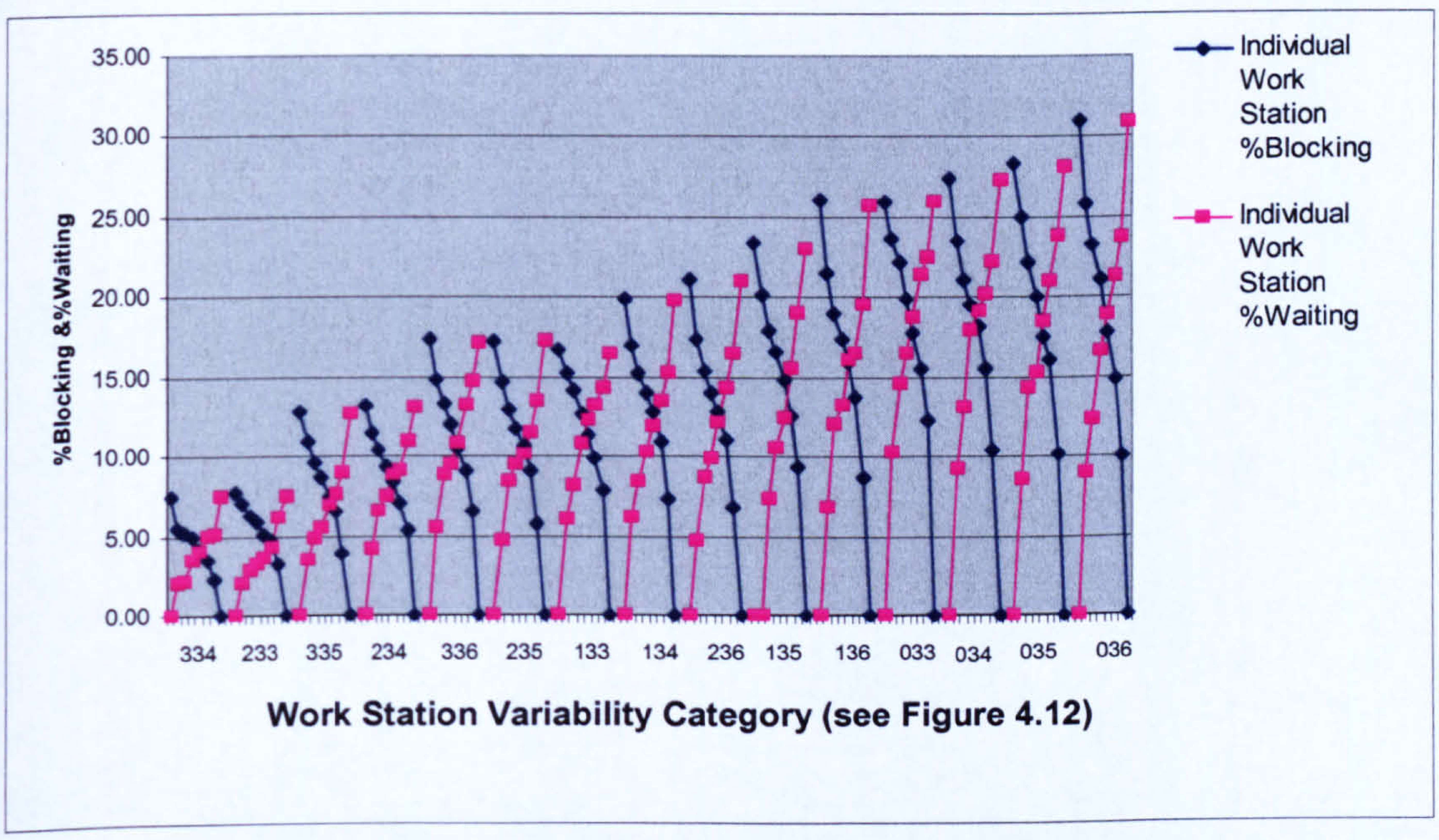

Figure 5.11: % Blocking and %Waiting on 13 Workstation Flow Lines: All results derived from Simulation Models

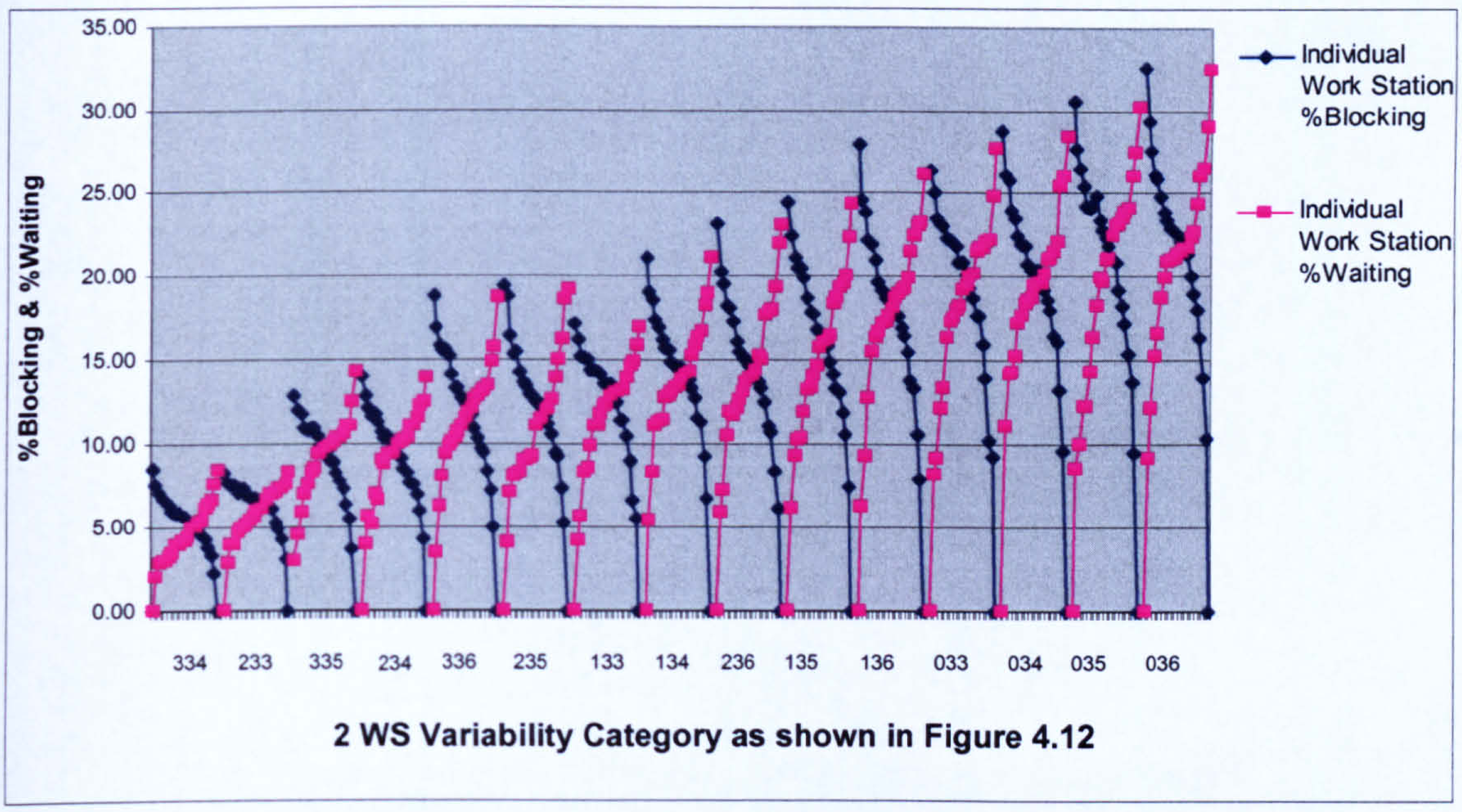

Figure 5.12: % Blocking and %Waiting on 21 Workstation Flow Lines: All results derived from Simulation Models

These data provided by the simulation results were used to develop estimating equations for using the *number of workstations* within a flow line and the *position of a workstation* within a flow line to calculate %Blocking arising at an individual workstation. These estimating models were developed in three stages:

Stage 1: Development of models for estimating $\%B_{1,n}$, i.e. the %Blocking on the first workstation of a multi-workstation flow line. Here the following models were developed:

$$C_{1,n} = 2.19 + (0.07.\ n) \qquad (24)$$

$$Cf_{1,n} = 1.45 + n \qquad (25)$$

$$\% B_{1,n} = C_{1,n} + (Cf_{1,n} \; . \; \%B_{1,2}) \qquad (26)$$

Where:

$C_{1,n}$ = Value of the constant calculated in Equation 24.
$Cf_{1,n}$ = Value of the coefficient calculated in Equation 25.
$\% B_{1,n}$ = %Blocking of the 1st workstation on an *n* workstation line.
n = Number of workstations on the line.

Maximum positive and negative differences between simulation and estimated values were used to determine estimating accuracy, i.e. these differences ranged between -2.50 and +2.76.

Stage 2: Development of models for estimating $\%B_{n-1,n}$, i.e. the %Blocking on the "last but one" workstation of a multi-workstation flow line. Note the %Blocking of the last workstation on the line is assumed to be zero. Here the following models were developed:

$$C_{n-1,n} = 0.43 + n \qquad (27)$$

$$Cf_{n-1,n} = 0.54 + n \qquad (28)$$

$$\% B_{n-1,n} = C_{n-1,n} + (Cf_{n-1,n} \; . \; \%B_{1,2}) \qquad (29)$$

Where:

$C_{n-1,n}$ = Value of constant calculated in Equation 27.
$Cf_{n-1,n}$ = Value of coefficient calculated in Equation 28.
$\% B_{n-1,n}$ = %Blocking of the 1st workstation on *n* workstation on line.

Maximum positive and negative differences between actual and estimated values were used to determine estimating accuracy, i.e. these differences ranged between -4.42 and +3.00.

Stage 3: Development of models for estimating $\%B_{2,n}$, to $\%B_{n-2,n}$, i.e. the %Blocking on workstations n = 2 to n = n - 2. Here the following models were developed:

$$S = (\% B_{1,n} - \% B_{n-1,n}) / (n-2) \quad (30)$$

For i = 2 to i = n – 2

$$\% B_{i,n} = \% B_{1,n} - (S \cdot (i-1)) \quad (31)$$

Where:

S = Rate of change of %Blocking between workstations, i.e. the slope.
i = Position of workstation in the line.
$\% B_{i,n}$ = %Blocking of the i^{th} workstation of a flow line *n* workstations in length.

Maximum positive and negative differences between simulation and estimated values were used to determine estimating accuracy, i.e. these differences ranged between -5.23 and +4.86. Figures 5.13 to 5.16 illustrate the close agreement achieved between estimated and simulation values.

Results from Trials 1 indicated that for flow lines containing workstations with common levels of variability the "sum of the %Blocking and % Waiting were approximately equal at all workstations along the line". Hence, knowledge of the %Blocking at each workstation along the line would enable the %Waiting to be calculated at individual workstations.

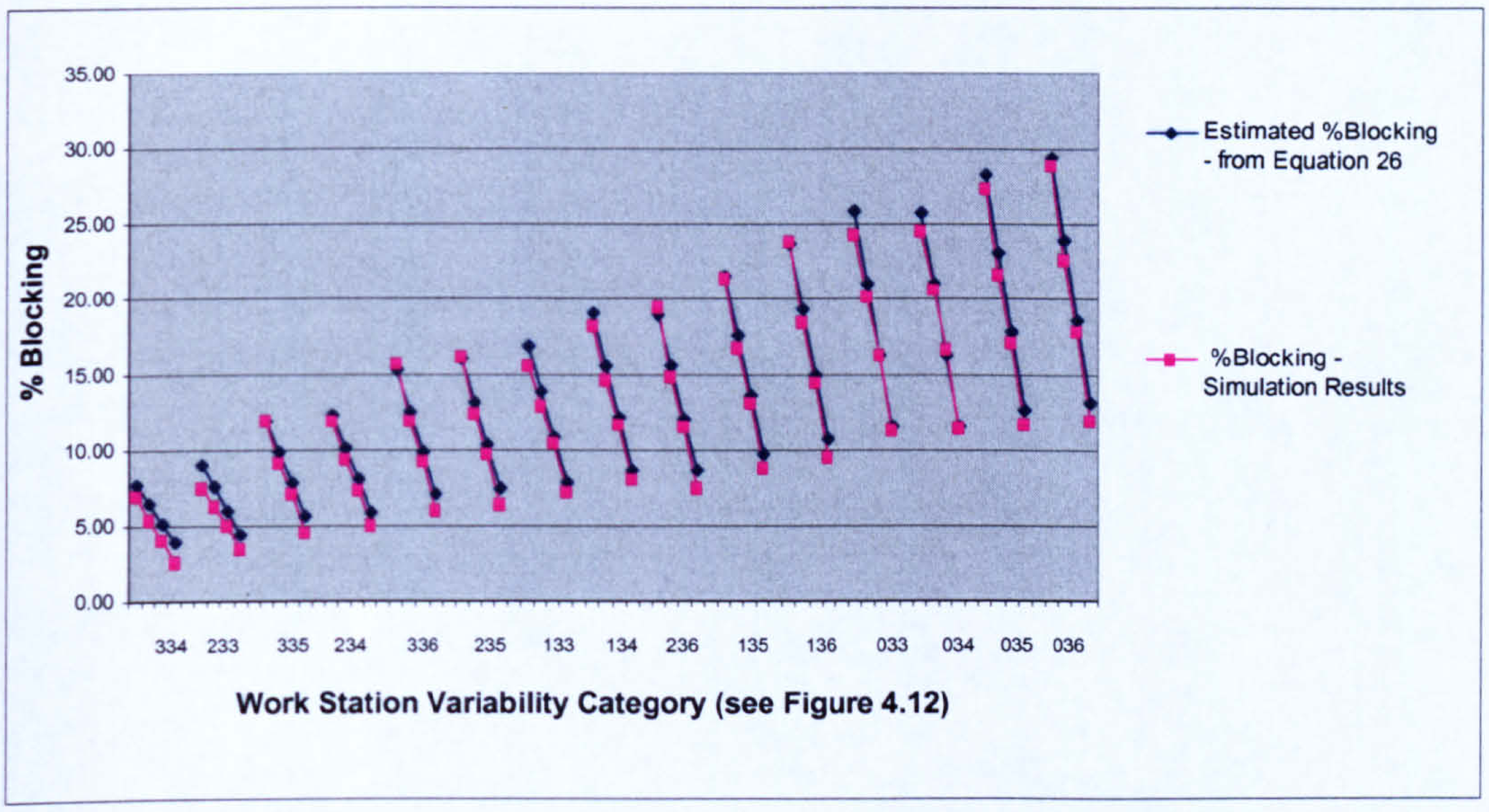

Figure 5.13: Comparison of Estimated & Simulated %Blocking on 5 Workstation Flow Lines: Zero Blocking on 5th Workstation

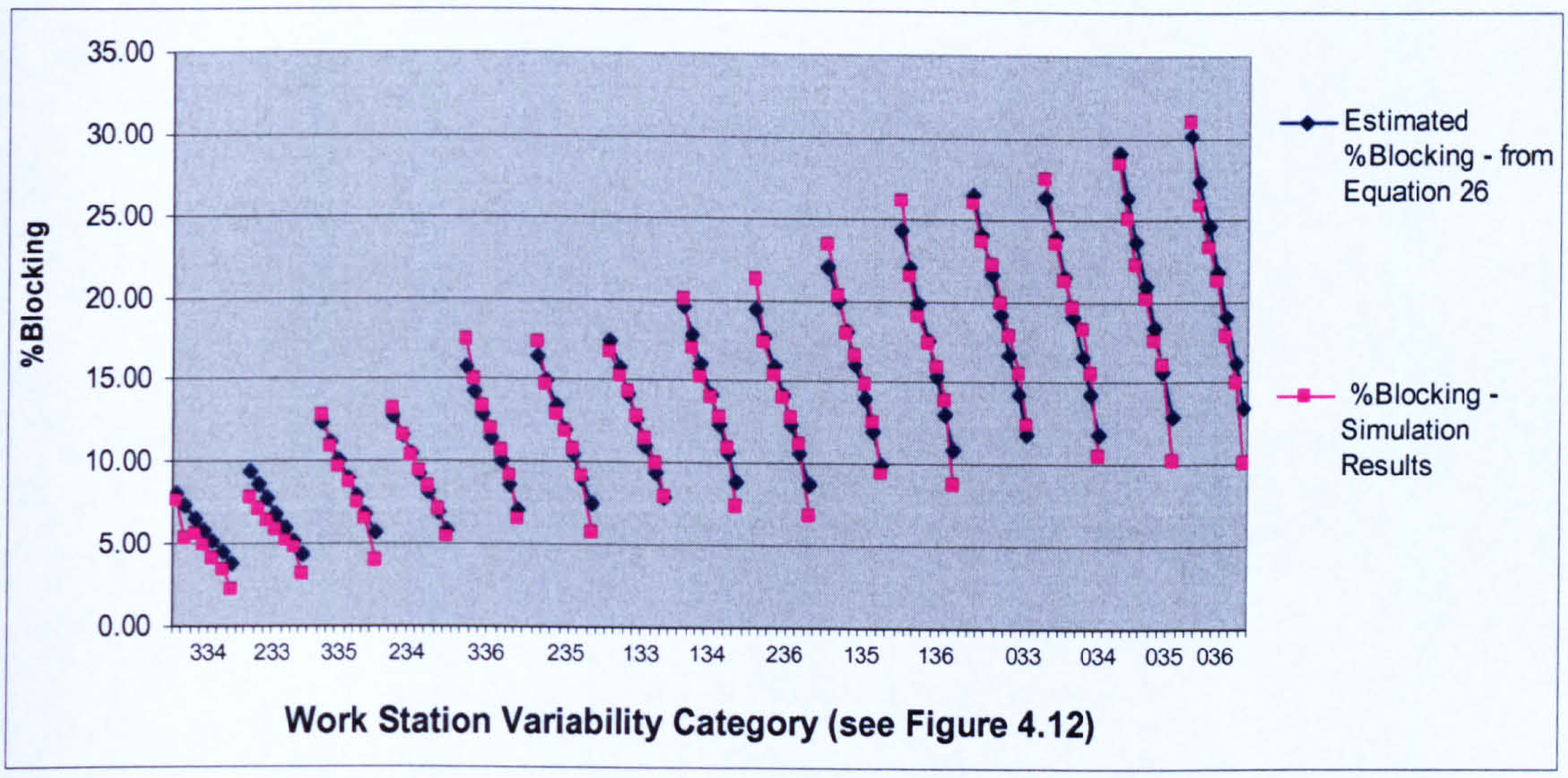

Figure 5.14: Comparison of Estimated & Simulated %Blocking on 8 Workstation Flow Lines: : Zero Blocking on 8th Workstation

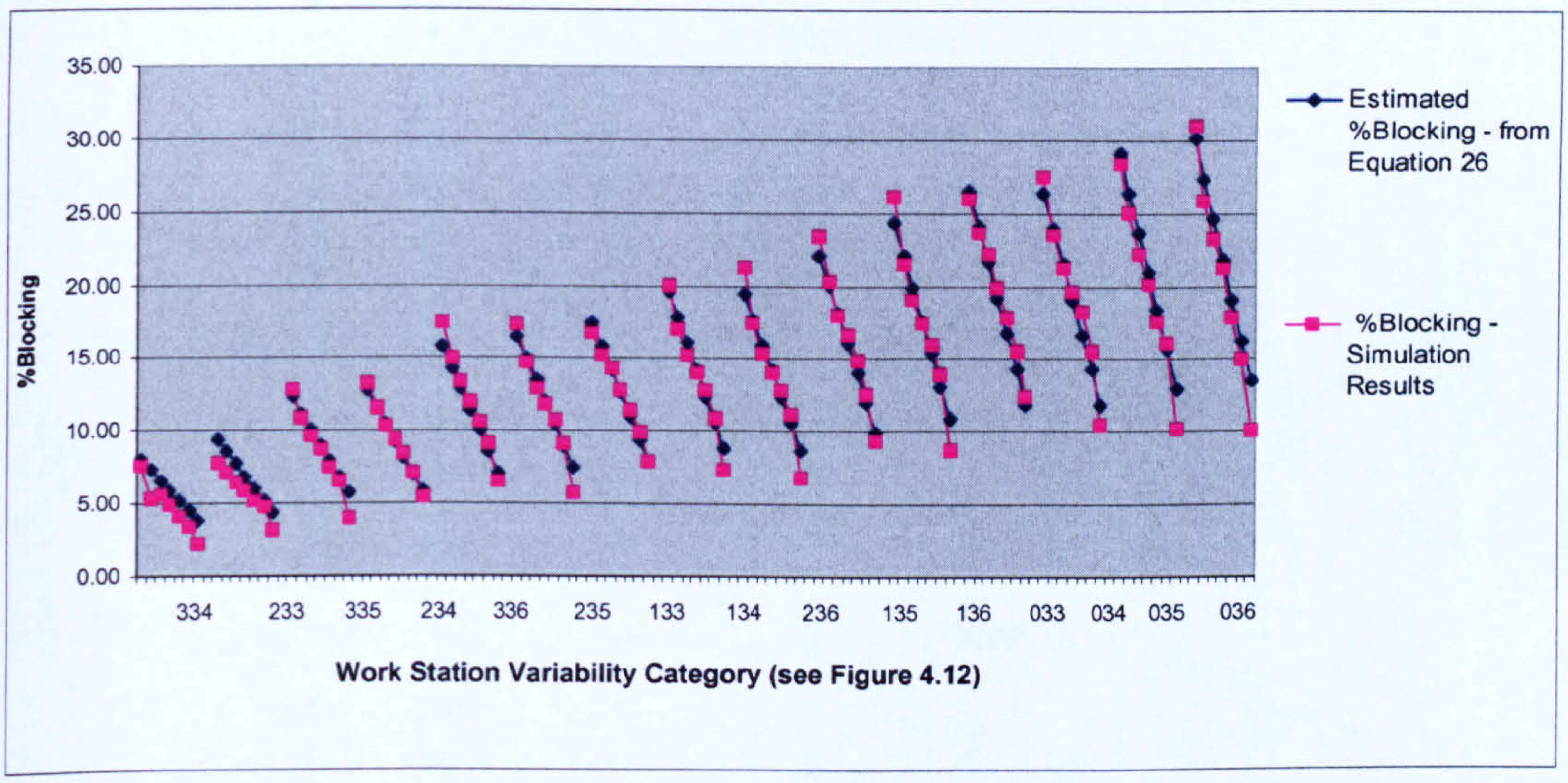

Figure 5.15: Comparison of Estimated & Simulated %Blocking on 13 Workstation Flow Lines : Zero Blocking on 13th Workstation

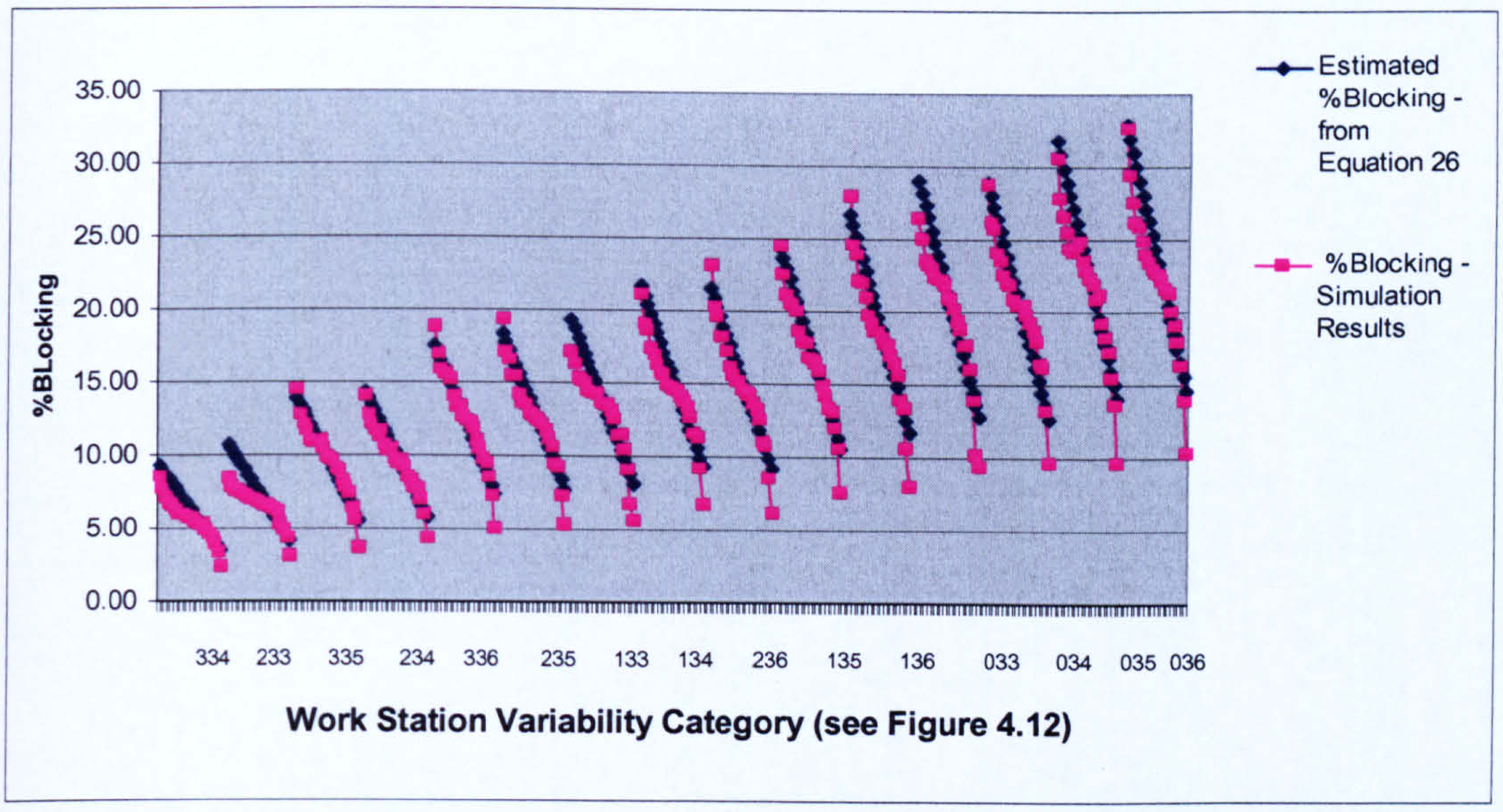

Figure 5.16: Comparison of Estimated & Simulated %Blocking on 21 Workstation Flow Lines: Zero Blocking on 21st Workstation

Trials 4: Here a series of trials were undertaken with the aim of identifying the effects of mixed levels of workstation variability within a flow line, i.e.:

i. Two-workstation lines were tested in which each workstation possessed different levels of variability as shown in Figure 4.12. This involved developing models for all combinations of pairs of the possible 15 categories identified in Figure 4.12, i.e. a total of 225 simulation models. Results from these simulation experiments are presented in Figure 5.17.

Preceding Workstation	Succeeding Workstation 033	034	035	036	133	134	135	136	233	234	235	236	334	335	336
033	A=C<B=D 16.58 16.68	A=C<B<D 23.33 11.77	A=C<B<D 31.46 8.03	A=C<B<D 36.97 6.44	A<C<B=D 20.88 7.42	A<C<B<D 28.39 4.72	A<C<B<D 35.42 3.06	A<C<B<D 41.03 2.34	A<C<B=D 26.47 1.83	A<C<B<D 33.66 0.84	A<C<B<D 40.13 0.52	A<C<B<D 45.31 0.38	A<B=C<D 39.00 0.01	A<B=C<D 45.04 0.01	A<B=C<D 50.05 0.00
034	A=C<D<B 11.28 24.04	A=C<B=D 16.52 17.72	A=C<B<D 23.88 12.40	A=C<B<D 29.14 10.01	A<C<D<B 14.56 14.15	A<C<B=D 20.62 9.44	A<C<B<D 27.23 6.34	A<C<B<D 26.40 8.48	A<C<D<B 18.63 7.16	A<C<B=D 24.94 3.70	A<C<B<D 31.48 2.35	A<C<B<D 36.99 1.68	A<C<B=D 30.63 1.02	A<C<B<D 36.73 0.47	A<C<B<D 41.89 0.33
035	A=C<D<B 8.14 31.23	A=C<D<B 12.20 24.33	A=C<B=D 18.33 17.67	A=C<B<D 22.84 14.47	A<C<D<B 10.59 21.39	A<C<D<B 15.24 15.56	A<C<B=D 21.08 10.99	A<C<B<D 26.38 8.65	A<C<D<B 13.84 13.93	A<C<D<B 18.77 8.75	A<C<B=D 24.63 6.09	A<C<B<D 30.01 4.45	A<C<D<B 23.63 4.74	A<C<B=D 29.36 2.76	A<C<B<D 34.60 1.87
036	A=C<D<B 6.16 37.33	A=C<D<B 9.39 30.63	A=C<D<B 14.39 23.21	A=C<B=D 19.10 18.87	A<C<D<B 8.04 28.04	A<C<D<B 11.65 21.66	A<C<D<B 16.63 16.42	A<C<B=D 21.30 13.24	A<C<D<B 10.71 20.26	A<C<D<B 14.84 15.11	A<C<D<B 19.50 10.94	A<C<B=D 24.39 8.41	A<C<D<B 18.77 9.85	A<C<D<B 23.68 6.57	A<C<B=D 28.47 4.79
133	C<A<B=D 7.53 20.87	C<A<B<D 14.13 14.80	C<A<B<D 21.99 10.38	C<A<B<D 28.07 8.25	A=C<B=D 10.29 10.25	A=C<B<D 17.86 6.43	A=C<B<D 25.52 4.21	A=C<B<D 31.94 3.19	A<C<B=D 14.86 2.77	A<C<B<D 23.06 1.19	A<C<B<D 30.63 0.75	A<C<B<D 36.55 0.50	A<B=C<D 29.89 0.01	A<B=C<D 36.38 0.01	A<B=C<D 41.69 0.01
134	C<A<D<B 4.48 28.40	C<A<B=D 8.90 21.33	C<A<B<D 15.65 15.18	C<A<B<D 21.49 11.95	A=C<D<B 6.26 21.28	A=C<B=D 11.84 11.74	A=C<B<D 18.38 8.10	A=C<B<D 6.22 24.60	A<C<D<B 9.20 9.31	A<C<B=D 15.37 4.87	A<C<B<D 22.32 3.14	A<C<B<D 28.67 2.14	A<C<B=D 20.98 1.36	A<C<B<D 27.78 0.64	A<C<B<D 33.62 0.43
135	C<A<D<B 3.03 35.32	C<A<D<B 6.17 27.94	C<A<B=D 11.35 20.80	C<A<B<D 16.03 16.90	A=C<D<B 4.22 25.12	A=C<D<B 8.16 18.51	A=C<B=D 13.55 13.43	A=C<B<D 18.93 10.46	A<C<D<B 6.35 16.83	A<C<D<B 10.77 10.74	A<C<B=D 16.53 7.46	A<C<B<D 22.26 5.51	A<C<D<B 15.12 5.86	A<C<B=D 21.05 3.45	A<C<B<D 26.73 2.35
136	C<A<D<B 2.21 41.16	C<A<D<B 4.59 34.08	C<A<D<B 8.58 26.36	C<A<B=D 12.30 22.02	A=C<D<B 3.06 31.74	A=C<D<B 5.98 24.98	A=C<D<B 10.16 19.01	A=C<B=D 15.09 14.91	A<C<D<B 4.67 23.75	A<C<D<B 7.98 17.13	A<C<D<B 12.48 12.89	A<C<B=D 17.57 9.86	A<C<D<B 11.49 11.55	A<C<D<B 16.29 7.82	A<C<B=D 21.27 5.69
233	C<A<B=D 1.84 26.51	C<A<B<D 6.79 19.44	C<A<B<D 14.03 13.81	C<A<B<D 20.38 10.80	C<A<B=D 2.76 14.57	C<A<B<D 9.17 9.47	C<A<B<D 16.75 6.35	C<A<B<D 23.65 4.76	A=C<B=D 4.80 4.74	A=C<B<D 13.05 2.20	A=C<B<D 20.94 1.32	A=C<B<D 27.81 0.94	A<B=C<D 20.06 0.00	A<B=C<D 27.13 0.01	A<B=C<D 33.26 0.01
234	C<A<D<B 0.82 33.92	C<A<B=D 3.60 25.88	C<A<B<D 9.14 18.95	C<A<B<D 14.63 15.64	C<A<D<B 4.95 15.75	C<A<B=D 20.59 3.23	C<A<B<D 10.97 10.93	C<A<B<D 17.24 8.33	A=C<D<B 2.20 12.70	A=C<B=D 7.11 7.07	A=C<B<D 13.94 4.55	A=C<B<D 20.66 3.17	A<C<B=D 11.70 2.02	A<C<B<D 18.91 1.02	A<C<B<D 25.24 0.66
235	C<A<D<B 0.49 40.23	C<A<D<B 2.31 31.93	C<A<B=D 6.18 24.53	C<A<B<D 10.45 20.05	C<A<D<B 0.75 30.45	C<A<D<B 3.06 22.69	C<A<B=D 7.44 16.60	C<A<B<D 12.66 13.00	A=C<D<B 1.33 21.08	A=C<D<B 4.37 14.25	A=C<B=D 9.72 9.59	A=C<B<D 15.26 7.19	A<C<D<B 7.51 7.65	A<C<B=D 13.26 4.59	A<C<B<D 19.19 3.11
236	C<A<D<B 0.34 45.53	C<A<D<B 1.61 37.22	C<A<D<B 4.40 30.09	C<A<B=D 7.74 25.20	C<A<D<B 0.50 36.87	C<A<D<B 2.14 28.96	C<A<D<B 5.37 22.39	C<A<B=D 9.47 18.10	A=C<D<B 0.89 27.97	A=C<D<B 3.07 20.82	A=C<D<B 6.79 15.56	A=C<B=D 11.75 11.59	A<C<D<B 5.34 14.02	A<C<D<B 9.69 9.68	A<C<B=D 14.63 6.98
334	C<A=D<B 0.00 39.99	C<A<B=D 0.93 31.38	C<A<B<D 4.79 23.55	C<A<B<D 9.45 18.96	C<A=D<B 0.00 29.69	C<A<B=D 1.27 21.33	C<A<B<D 5.77 15.12	C<A<B<D 11.38 11.58	C<A=D<B 0.00 19.97	C<A<B=D 1.98 11.81	C<A<B<D 7.41 7.57	C<A<B<D 13.87 5.41	A=C<B=D 3.86 3.82	A=C<B<D 10.79 2.07	A=C<B<D 17.63 1.25
335	C<A=D<B 0.00 45.36	C<A<D<B 0.50 37.43	C<A<B=D 2.89 29.08	C<A<B<D 6.41 23.97	C<A=D<B 0.00 36.53	C<A<D<B 0.64 27.45	C<A<B=D 3.51 20.93	C<A<B<D 7.85 16.56	C<A=D<B 0.00 27.32	C<A<D<B 1.04 19.15	C<A<B=D 4.76 12.97	C<A<B<D 9.63 9.88	A=C<D<B 2.01 11.03	A=C<B=D 6.83 6.73	A=C<B<D 12.32 4.64
336	C<A=D<B 0.00 49.74	C<A<D<B 0.31 42.58	C<A<D<B 1.97 34.33	C<A<B=D 4.50 28.94	C<A=D<B 0.00 41.23	C<A<D<B 0.42 33.72	C<A<D<B 2.37 26.57	C<A<B=D 5.64 21.62	C<A=D<B 0.00 33.29	C<A<D<B 0.63 25.26	C<A<D<B 2.99 19.44	C<A<B=D 6.95 14.93	A=C<D<B 1.31 17.82	A=C<D<B 0.00 12.59	A=C<B=D 9.18 9.04

Actual % Waiting — Actual % Blocking

Figure 5.17: %Blocking and %Waiting 2WS Lines

Correlation coefficients were used to compare the actual workstation %Blocking and %Waiting levels arising from the simulation models with variability means, geometric means, harmonic means, PERT means, standard deviations, coefficient of variations and the medians of the workstation cycle time variability. Results are provided in Table 5.7 where it can be seen that of the statistical measures listed in Table 5.7 the *"the ratio of the 2nd to 1st workstation PERT mean values"* provides the greatest level of correlation with %Blocking but no statistical measure is highly correlated with %Waiting.

Statistical Measure	% Blocking	% Waiting
1st WS Mean	-0.75	0.54
2nd WS Mean	0.56	-0.38
2nd WS/1st WS Means	0.96	-0.63
1st WS Geometric Mean	-0.67	0.35
2nd WS Geometric Mean	0.36	-0.48
2nd WS/1st WS Geometric Means	0.67	-0.40
1st WS Harmonic Mean	-0.65	0.32
2nd WS Harmonic Mean	0.34	-0.49
2nd WS/1st WS Harmonic Means	0.57	-0.30
1st WS PERT Mean	-0.75	0.54
2nd WS PERT Mean	0.96	-0.48
2nd WS/1st WS PERT Means	0.99	-0.52
1st WS Median	-0.52	0.49
2nd WS Median	0.49	-0.29
2nd WS/1st WS Medians	0.78	-0.52
1st WS Standard Deviation	0.13	0.14
2nd WS Standard Deviation	0.13	0.31
2nd WS/1st WS Standard Deviations	-0.03	0.08
1st WS Coefficient of Variation	0.45	-0.10
2nd WS Coefficient of Variation	-0.11	0.42
2nd WS/1st WS Coefficient of Variations	-0.31	0.28

Table 5.7: Correlation Coefficient Values for Statistical Measures And % Blocking and % Waiting on 2 Workstation Flow Lines

These data provided by the simulation results were then used to develop estimating equations for using the *ratio of the 2^{nd} to the 1^{st} workstation* PERT Means to calculate %Blocking and %Waiting arising from a specific variability category. The following models, (i.e. Equations 32 and 33), were developed again using the Genehunter GA package (Lewinson, 1995) to analyse the data and determine relationships that minimised error range.

$$\% B_{1,2} = -9.22 + (11.57 \,.\, rPM_{1,2}) \qquad (32)$$

Where:

$rPM_{1,2}$ = The ratio of the 2^{nd} to 1^{st} the workstation PERT means.

Maximum positive and negative differences between simulated and estimated values using Equation 32 ranged between -7.12 and +4.36.

$$\% W_{2,2} = 32.75 + (-8.82 \,.\, rPM_{1,2}) \qquad (33)$$

Maximum positive and negative differences between simulated and estimated values using Equation 33 ranged between -18.31 and +23.30.

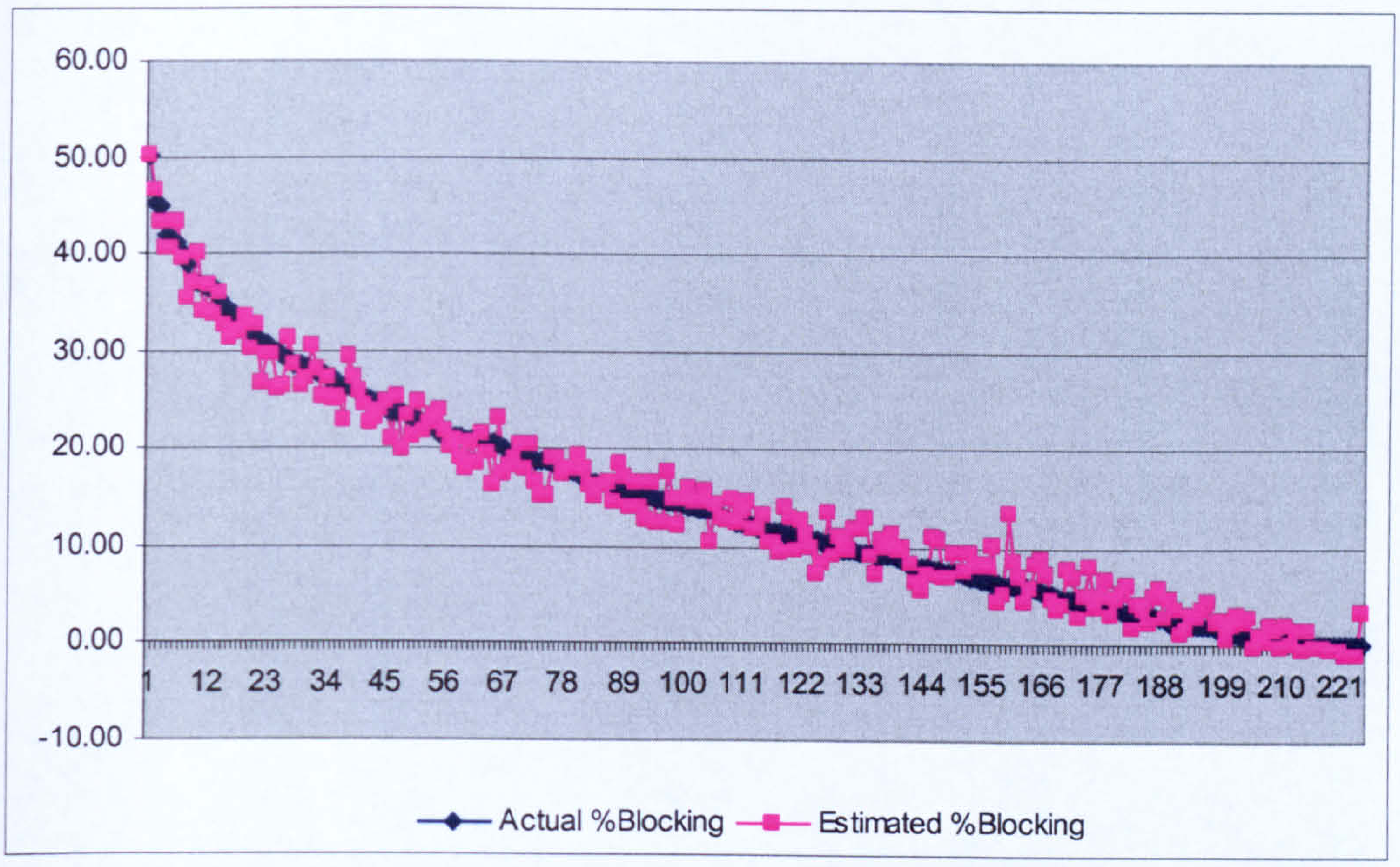

Figure 5.18: Actual Vs Estimated % Blocking for 2WS Mixed and Common Variability (Using 2nd WS /1st WS PERT Means as Predictor Variable)

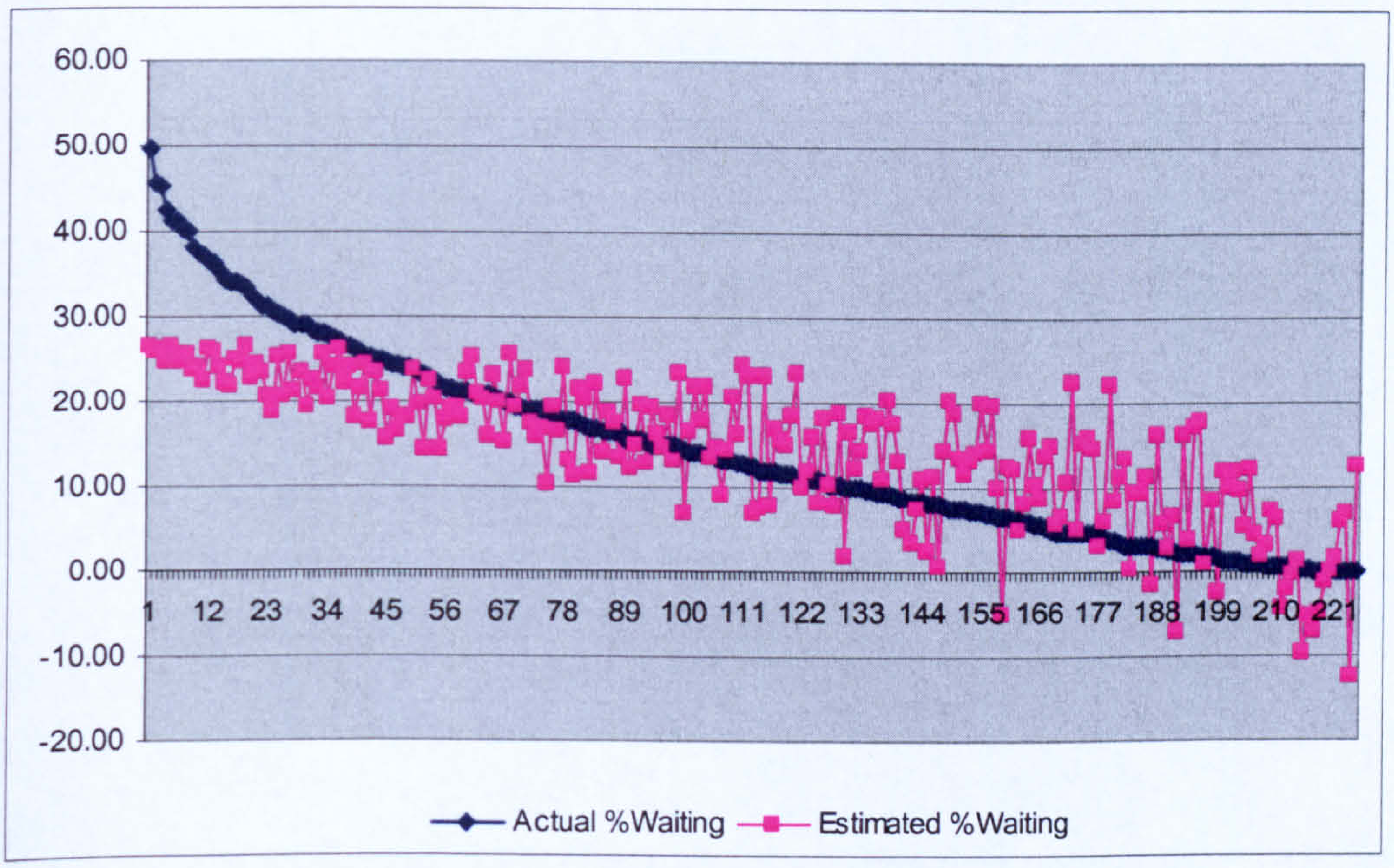

Figure 5.19: Actual Vs Estimated % Waiting for 2WS Mixed and Common Variability (Using 2nd /1st PERT Means as Predictor Variable)

ii. The remaining experiments identified in Chapter 4 and represented in Table 5.8 were designed to explore the effect of mixed levels of variability on %Blocking and %Waiting levels. Typical results for these experiments are shown in Figure 5.20 to 5.24 the full results provided in Appendix and observations are discussed in Chapter 6

Primary Levels of Variability		Secondary Levels of Variability		No of WS with varability	No of Models
Level	Position	Level	Position		
036	mixed as shown in firgure 5.20	033	mixed as shown in firgure 5.20	1	5
036	mixed as shown in firgure 5.21	033	mixed as shown in firgure 5.21	2	5
033	mixed as shown in firgure 5.2	033	mixed as shown in firgure 5.2	3	3
036	mixed as shown in firgure 5.23	033	mixed as shown in firgure 5.23	4	2
mixed	mixed as shown in firgure 5.24	mixed	mixed as shown in firgure 5.24	21	1

Table 5.8: Mixed Variability Experiments

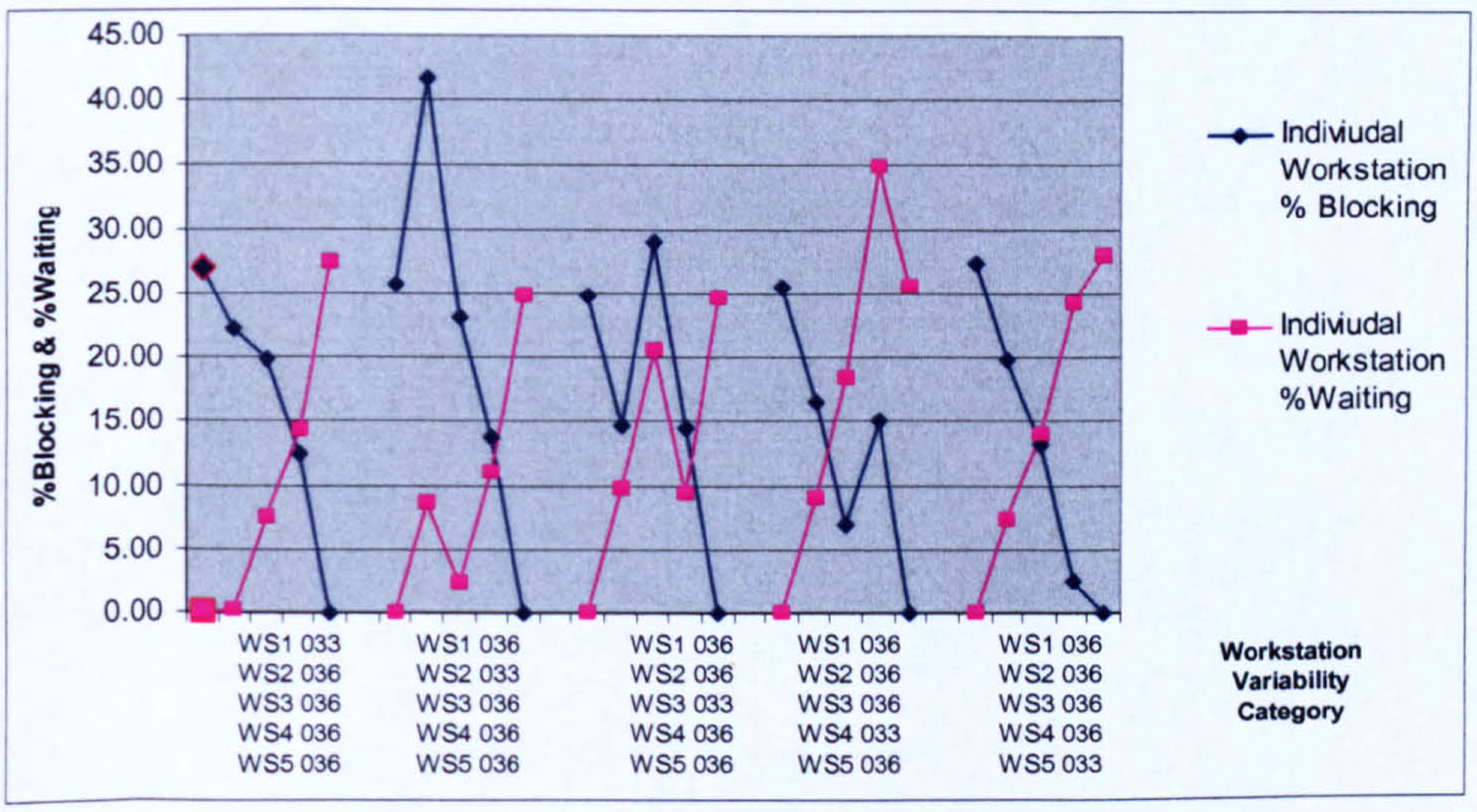

Figure 5.20: Figure 5.4 %Blocking and %Waiting on 5WorkStation Flow Lines: Mixed Workstation (WS) Variability: All results derived from Simulation Models

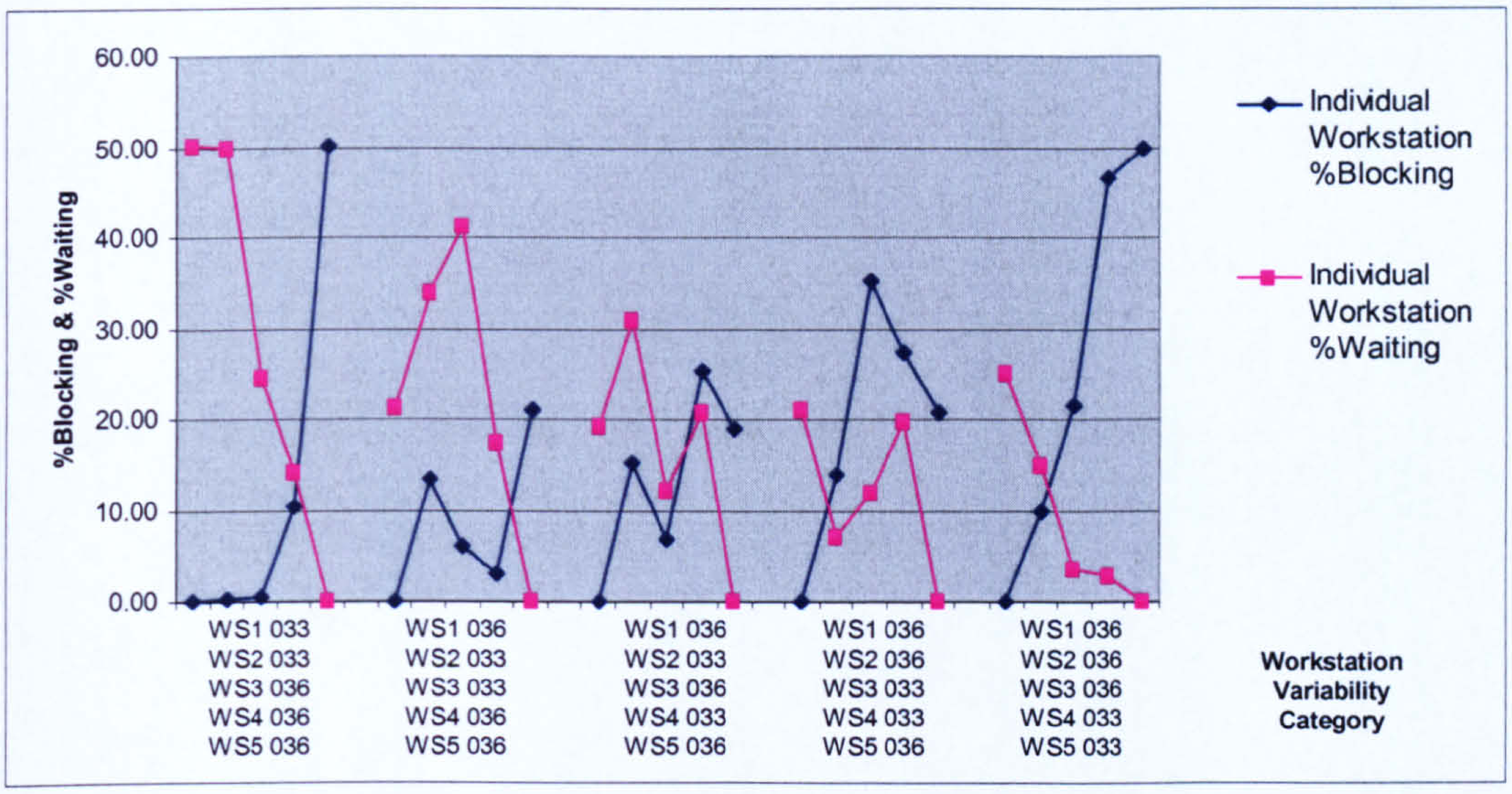

Figure 5.21: %Blocking and %Waiting on 5Workstation Flow Lines: Mixed Workstation (WS) Variability: All results derived from Simulation Models

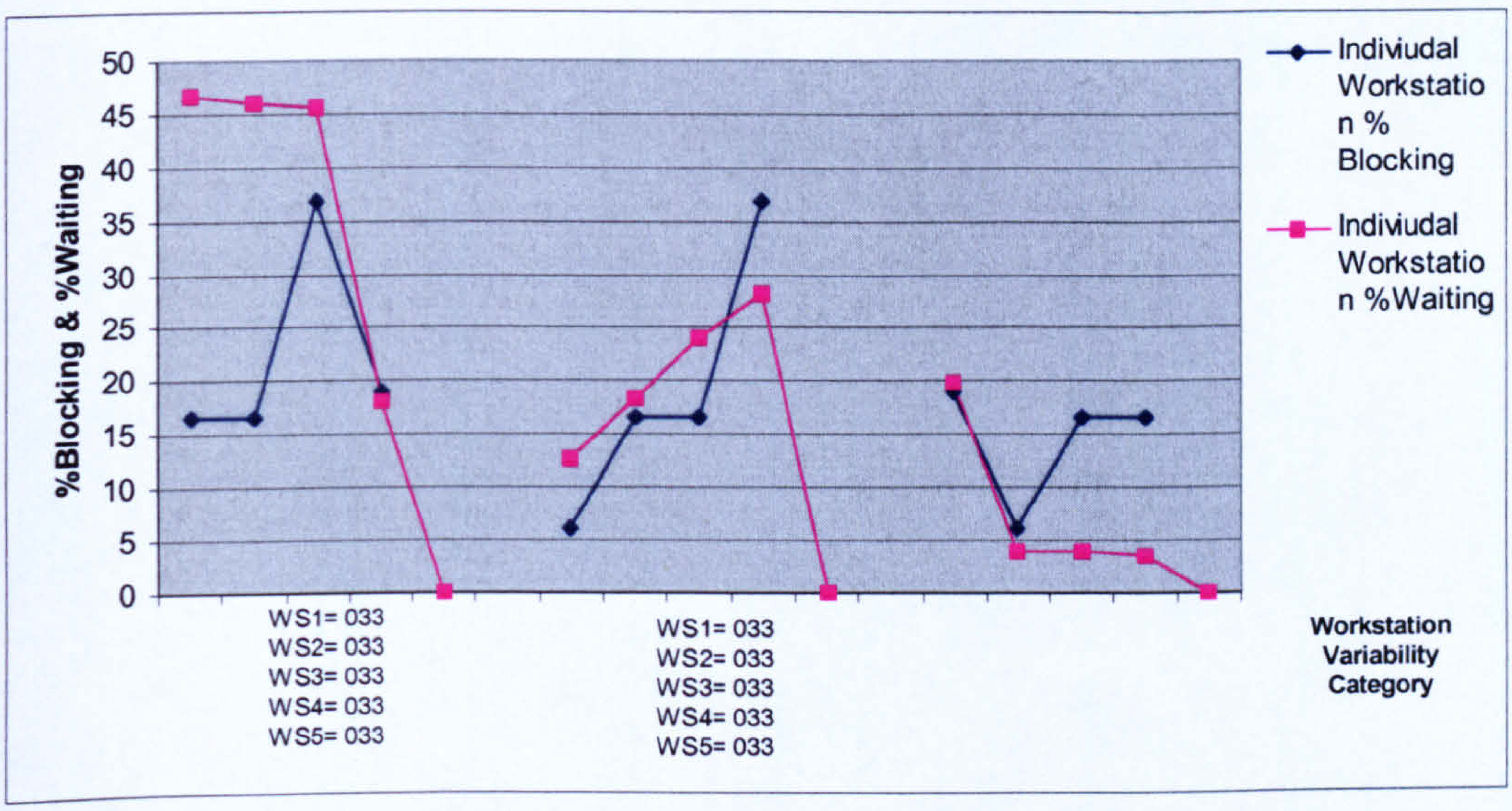

Figure 5.22: %Blocking and %Waiting on 5Workstation Flow Lines: Mixed Workstation (WS) Variability: All results derived from Simulation Models

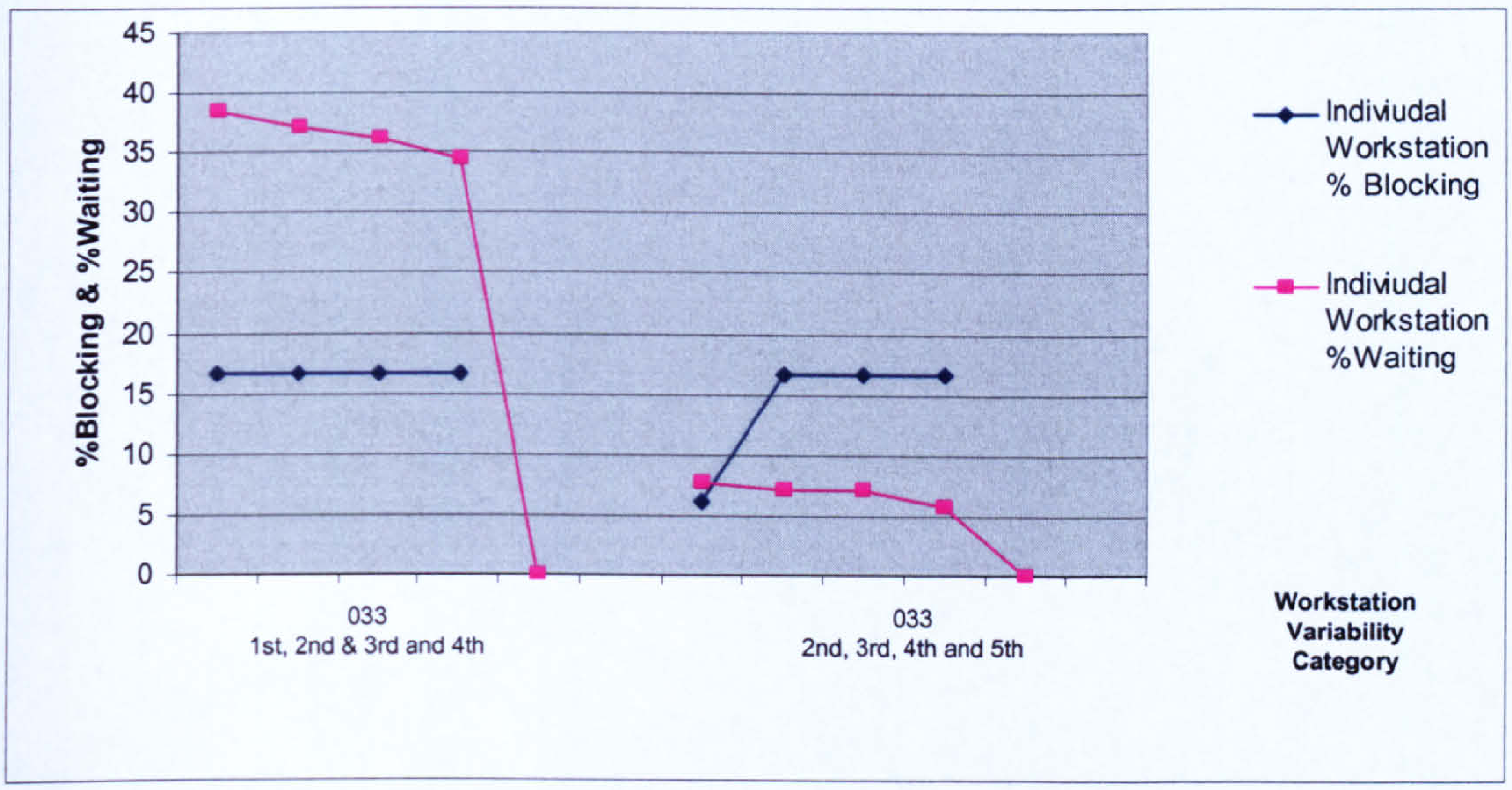

Figure 5.23: %Blocking and %Waiting on 5Workstation Flow Lines: Mixed Workstation (WS) Variability: All results derived from Simulation Models

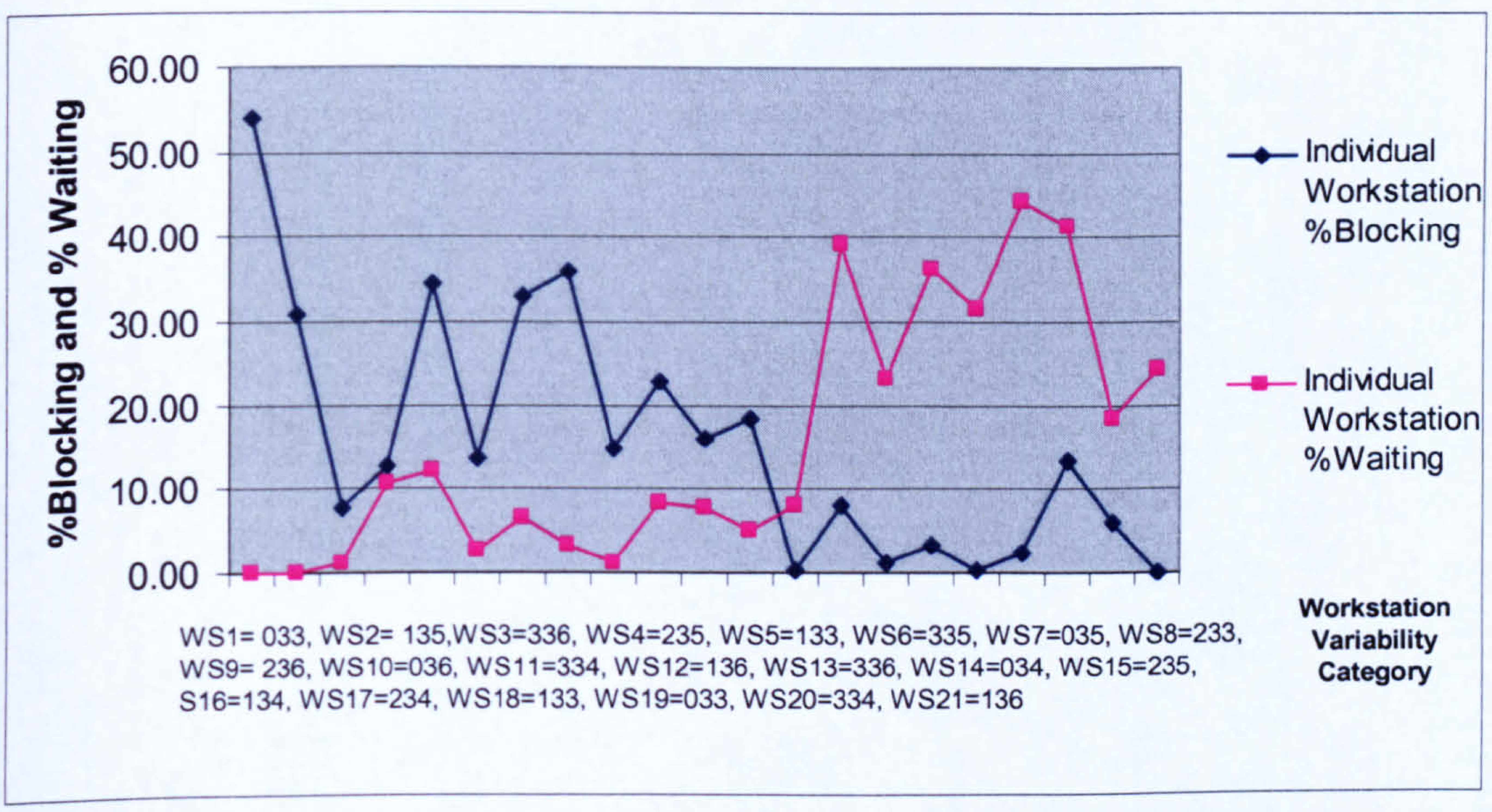

Figure 5.24: %Blocking and %Waiting on 21Workstation Flow Lines: Mixed Workstation (WS) Variability: All results derived from Simulation Models

Chapter 6 Discussion

6.1 Introduction

Black (1991) has argued that for a company to successfully compete in today's market environment its manufacturing system must possess the ability to maintain high levels of quality and delivery reliability and produce at low cost. Within high volume/low variety manufacturing environments these conditions are normally achieved through the use of flow processing. Such systems have been in existence since their initial adoption by Ford (1988).

However, the conditions under which flow processing lines need to operate have changed drastically since Ford (1988) introduced this concept of manufacture. In general these changes have lead to the need, on individual flow lines, to process wider ranges of products and with wider variation in throughput rates. Black (1991) argues that such changes, i.e. providing increasing levels of product variety and flexibility in terms of production volumes, are increasingly necessary to maintain competitiveness. The wide spread introduction of lean principles, particularly within high variety/low volume manufacturing environments, and their reliance on flow processing is again accelerating the pace at which these changes need to take place. There is now the need for flow processing lines to deal with the following, i.e.:

a. greatly increased TAKT times, for example measured in hours, shifts and often days rather than minutes,

b. wider range of work contents within individual workstations through their need to process or assemble product options,

c. within a workstation a wider variation in work content between individual TAKT cycles,

d. increased frequency of product change-overs and greater variation of change-over times,

e. incorporating equipment service, planned and breakdown maintenance activities within TAKT cycles, and

f. reduced dependence on use of buffer stocks to de-synchronise flow lines.

The aim of the current work has been to examine how flow lines can be designed to cope efficiently with the above constraints. In this respect the research objectives were to enable existing methods of dealing with variability to be implemented more effectively through increased knowledge of the affects of such variability on flow processing lines. In terms of the methods available for dealing with variability, Section 3.6, the main methods considered were line balancing, (i.e. allocation of tasks to workstations), sequencing items onto the flow line, removing causes and reducing levels of variability, (e.g. using continuous improvement and set-up reduction techniques), variability pooling and the use of flexible labour. Knowledge of the levels of *blocking* and *waiting* arising at individual workstations is essential to deciding which of the above methods to use and to plan and control the use of an individual method. This research has, therefore, focussed on developing methods by which such levels of *blocking* and *waiting* can be determined.

6.2 Flow Processing and Variability

The traditional method of achieving high product variety and production volume flexibility, (i.e. batch production using process based layouts), normally possesses problems in achieving delivery reliability, low costs and reliable quality levels (Evans el. al. 1990). Flow processing offers greater benefits in these areas but their effectiveness depends on the ability to design, plan and control effective flow lines that do not experience the significant reductions in manufacturing efficiency that are normally associated with higher levels of product and demand variability.

Normally, however, traditional flow processing systems are designed to cope efficiently only within the conditions for which they were initially designed, i.e. typically design constraints include stable demand, high and limited range in production volumes, limited variability in product mix ratios, limited range of processes, limited range of tooling, limited process route options, continuous production, and single product types or a limited range of products that are similar in design. Limitations to product, process and demand variability are, therefore, built into the system from the initial design. If the requirements of the cell change due to variations in product mix, variations in volume or introduction of new products, the effects on the operation of the cell can result in poor utilisation of processing resources, over utilisation of other resources and the inefficient use of manning, (Sethi et. al. 1990). The work of Sethi et. al. highlights the need to make use, particularly of flexible labour, to enable flow lines to cope with such product mix and volume changes. The current research, through its development of methods for calculating levels of blocking and waiting seeks to assist in this area.

Attempts at introducing flow processing to high variety/low volume manufacturing environments currently focus on the development of methods of minimising the levels of variety and increasing the production volumes that the flow line are designed to manufacture. The implementation of flow manufacturing has, therefore, traditionally been through the use of cellular manufacture. Such systems incorporate practices from both batch and flow processing systems (Clarke et. al. 1993) and depend on the ability to reduce product and process variability through the use of Group Technology to identify part families. The ability to reduce variability in this way can no longer be assured in market environments that are demanding ever increasing levels of product choice.

Of the flow line characteristics listed in Table 2.2 it is perhaps the need for regularity of material flow through the line that is currently the most difficult to achieve. In this respect most other flow line characteristics have an effect on regularity of material flow, i.e.:

a. work areas are not laid out in a sequential manner, predetermined routes not provided for products through sequentially dependent work centres, layout of the work areas not designed to minimise the distances moved by materials, and/or layout of the work areas not designed to provide visibility between workstations then increased variability normally occurs in terms of handling and transport times between workstations,

b. if balanced work contents and labour allocation are not provided for each work area, equal cycle times not provided for each work area, fixed cycle times not allocated to each work area that are as near to, but not greater then, the TAKT time, and/or operators not provided that perform a limited range of well defined and specialised work tasks then variability normally occurs in terms of work task times within workstations, and

c. if a high level of process reliability is not possible, planned maintenance of equipment not undertaken out of production hours, high levels of process capability possible to avoid need to rework components or scrap components off the line, and/or if minimum set-up times are not possible then variability normally occurs in terms of frequency and durations of change-overs, planned maintenance activities, breakdown maintenance activities and rework levels.

Regularity of material flow is normally designed into the flow line through the effective allocation of work tasks to workstations, i.e. line balancing. Heuristics methods are generally used in practice to design balanced flow lines including Kilbridge and Wester (1961), Arcus (1966) and Helgerson and Birnie (1961). However, the presence of product, process and demand variability results in variability of handling, waiting and work activity times. Under these circumstances allocating equal amounts of work to each workstation along the flow line is difficult resulting in lack of material flow synchronisation between workstations. Existing methods of designing flow processing lines are normally unable to design efficient lines since they need to assume that no variability exists and such events as equipment change-over and breakdowns do not occur. Line balancing techniques that attempt to consider variability during the line balancing process normally adopt TAKT times that possess a limited probability of being exceeded in practice by a single workstation task time (Kottas and Lau 1976, 1981, Sphicas and Silverman 1976, Henig 1986, Carraway 1989). Such techniques effectively introduce additional idle time, and therefore system inefficiency, to those work areas with high levels of variability. Although Arden-Finch, (2000) pointed out that due to time and resources limitations flow lines are often designed on the basis that they will be continuously improved throughout their operational life such an approach can only deal effectively with minor improvements in line design and operation. As the literature indicates existing line balancing techniques can not design efficient flow lines when high levels of variation are present. However, it can be assumed that greater knowledge of the effects of variation, (i.e. particularly levels of blocking and waiting), on the utilisation of individual workstations within a flow line will enable improved allocation of tasks to workstations such that other methods of coping with variability effects, (eg flexible labour), can be more effectively implemented.

The assumption that variation is 'everywhere', (Goldratt 1984, Hopp and Spearman 1996 and Davis 2000), is effectively correct since most resources and activities cannot be precisely controlled within a manufacturing environment such as to prevent some degree of variation occurring. Although within the literature associated with the existence and effects of variability various terms are used to describe the types of variation that exist the assertion of Hopp and Spearman, (1996) that only two types of variation exist, i.e. random and controllable, has been found to be true. Analysis of the wide range of definitions that exist in the literature has enabled a more precise method of defining individual types of variation to be established, Section 3.3. This method requires information concerning three factors, i.e.:

i. The time when the event occurs that causes the variation.
ii. The length of time over which the event causing the variation exists.
iii. The level of variation caused by the event.

For each of these factors information is required to resolve the following questions, i.e.:

i. Are they predictable?
ii. Is their cause known?
iii. Are methods available for controlling them?

The use of this method would provide valuable information with which to provide direction during the decision making and problem solving stages of continuous improvement exercises aimed at removing or reducing the effects of individual sources of variation. For example, the method would provide a detailed definition of the problem to be solved and alternative methods of resolving the problem.

It has been argued that the constraints under which flow processing lines operate need to dramatically change if they are to cope with changing market requirements. Greater levels of variability need to be effectively managed without significant loss in system performance. In addition to line balancing and sequencing a number of other basic strategies have been identified for dealing with the effects of variability i.e.:

i. remove or reduce levels of variability, e.g. using continuous improvement techniques, TQM, TPM, SMED and standard operations,

ii. pooling variability using queue sharing and/or resource sharing, and

iii. use of flexible resources, i.e. short term flexibility of processing equipment and operators that can react to the changes in task types and work contents that occur between batches.

The research objectives have been focussed on providing each of the above methods with the levels of information required for effective implementation, i.e.:

i. When removing or reducing levels of variability it is necessary to initially determine the actual levels of variability within individual workstations in order to prioritise improvement actions. Here the experimental work described in Section 4.3.1 was carried out in order to develop a method for combining individual sources of variability within a workstation into a single probability distribution. In this way the effects of individual sources of variation on overall workstation variability can be identified and used to direct improvement efforts. In addition, the relative levels of variability of workstations within the flow line can be compared and again improvement activities directed at workstations with the highest levels. The experimental work, Section 5.3, designed to develop a method of calculating the levels of blocking and waiting arising at individual workstations along a flow line, as a result of workstation variability, is also of use in determining where improvement activities should be directed, i.e. at those workstations exhibiting high levels of blocking, waiting or both.

ii. Pooling variability requires batching together individual work tasks that exhibit task time variability such that when undertaken within a single workstation the resulting relative variability levels of the batch completion times are less then those of individual work tasks. Here it is necessary to determine the levels of variation of individual work tasks in order that they can be batched, (i.e. collected together), within specific workstations in a manner that provides the pooling effect. Combining individual sources of variability within a workstation into a single probability distribution is essential to providing the necessary information to undertake work task pooling. Again the experimental work described in Section 4.3.2 was intended to develop a method of providing this information.

iii. When providing flexible resources it is essential that the effects of variability are determined such that informed decisions can be made concerning the timing and place for the movement of these resources. Calculating the levels of blocking and waiting arising at individual workstations along a flow line, as a result of workstation variability, provides essential information for making these decisions. The method developed using the experiments described in Section 5.2 provide information that can be applied in the early stage of designing a flow line where the work tasks allocated to each workstation can be determined based on the resulting need for resource flexibility. It can be also applied within existing flow lines where operators can move from an upstream workstation with high levels of waiting to a downstream workstation that possesses high levels of blocking, and by moving operators from a downstream workstation with high levels of blocking to an upstream workstation that possesses high levels of waiting.

Overall, therefore, in order to deal with increasing levels of variability within flow processing lines using one or more of the above strategies it is necessary to be able to measure the levels of variability in the areas listed in Table 6.1.

i. Levels of variability of individual work tasks. ii. Levels of variability of individual workstations. iii. Effects of differences in workstation variability on individual workstation utilisation.

Table 6.1 Areas for Variability Measurement

By knowing the information listed in Table 6.1 appropriate methods for dealing with variability can be designed into the flow processing line. Hence, the current research is intended to investigate how variation effects flow processing efficiency in order to provide methods for providing this information. In this respect the literature survey identified a number of attempts at measuring the effects of variability on flow line efficiency. However, none of this research addressed the three areas listed in Table 6.1 in sufficient detail as to provide solutions to their measurement. In this respect past research work has been limited in terms of its application to the current research objectives as follows:

a. A range of probability distributions have been investigated including normal distributions (Wild and Slack 1973, El-Rayah 1979), exponential distributions (Hunt 1956, Conway et. al. 1988, Hillier and So 1993), and Erlang distributions (Hillier and So 1993). It can be seen from this work that the focus of individual researchers on using actual probability distribution types has lead to this diverse range of distribution types being investigated. However, the use of actual probability distributions makes it difficult to combine different sources of variability that possess differing distribution types. Hence, the use within this current research of a single distribution type, ie the triangular distribution, to ease this problem. In all past research no attempt has been made to combine individual sources of variability into single probability distributions for individual workstations as in the current work. Hence, variability in workstation times has primarily resulted from variability in task times. No attempt has been made to include time variability involved in set-ups, equipment breakdowns and planned maintenance activities since it has always been assumed that line stoppages will occur for these to take place or they are undertaken outside the normal operating periods.

b. The number of workstations included within the flow lines investigated ranged from a minimum of 2 workstations (Hunt 1956, Anderson and Moodie 1968) to a maximum of 20 workstations (Payne, Slack and Wild 1972). Although this is a fairly wide range the past research undertaken does not provide information concerning the effect of line length, i.e. in terms of the number of workstations within the flow line, on levels of variability that arise within flow lines. Hence, neither does it provide indications of how levels of variability change for line lengths greater then 20 workstations. The effect of line length on levels of variability was, therefore, unknown when beginning the experimental stage of the current research. Hence, the need to undertake initial experiments using flow lines of 5, 7 and 9 workstations in length. The results obtained from these initial experiments were used to inform the design of later experiments such that sufficient data could be generated from which to quantitatively determine the effects of line length on variability levels.

c. Although several researchers (Blumenfeld 1990, Hillier and So 1993) examined lines with zero buffer stocks they did so merely to provide benchmarks for comparison with lines with varying levels of non-zero buffers. No detailed investigation of the effects of time variability on flow lines with zero buffers has taken place. The current research is concerned with the use of flow processing lines in manufacturing environments where it would be difficult or uneconomical to introduce buffers. Hence, the focus has been on examining the effects of variability where no such inter-workstation buffers are allowed.

d. The performance metrics used to measure efficiency were, in general, restricted to measuring overall line efficiency in terms of system utilisation, levels of work in progress and throughput quantities per time period. No detailed investigation has been undertaken to examine the effects of variability on individual workstations along a flow line such that their relative amounts of blocking and waiting can be estimated. It has been identified that this information is essential to the effective implementation of methods of dealing with the effects of this variability. For example through the deployment of flexible labour and/or equipment resources. This current research has attempted to resolve this lack of knowledge and has undertaken experiments from which mathematical models can be developed for estimating % Blocking and % Waiting for individual workstations at various positions, within flow lines of varying lengths.

6.3 Measuring Variability Levels of Work Tasks and Workstations

In order to be able to measure variability it has to be quantified. A wide range of probability distribution types, for describing variation, have been identified with many of them occurring within manufacturing environments. Ideally it is important to correctly identify the probability distribution type that exactly describes the actual distribution that exists in practice. Previous research provides little assistance in this direction since a variety of distribution types have been investigated. In addition, where specific distributions have been used the authors only suggest that these may be truly representative of the actual distributions. Although Ebeling, (1996) states that the correct probability distribution is important so as to have accurate results, in the context of the current work this statement may not be applicable. In this respect, identifying the precise distribution type that applies in practice requires the observations of work being carried out and the collection and analysis of real activity time data. Such observations can be both time and resource intensive. In addition, they are often subject to bias in the randomness of the times when observations are taken, the level of experience and motivation of the operators being observed and the standardisation of the work methods used.

In addition, it is possible that each individual probability type is valid only under the particular set of conditions observed. Should these conditions change then the probability type and characteristics may become invalid. Regular checks would, therefore, need to be carried out to ensure that changes had not occurred that adversely affected the suitability of the probability distribution type being used. Choosing a distribution type, therefore, can resolve into trade-offs between the degree of accuracy required from the results and the effort required to accurately determine both the probability distribution type and values for the measures that quantitatively define the distribution, e.g. the mean and standard deviation of the normal distribution. It is primarily for this reason that the Triangular distribution has been chosen since this type of distribution provides an acceptable trade-off between accuracy of results and ease of estimation of the distribution parameters.

When quantitatively defining probability distributions three basic values need to be determined, i.e.:

a. measure of its central tendency,

b. measure of the level of variation of its individual values, i.e. their dispersion, and

c. measure of the how individual values are skewed about the measure of central tendency.

This research has identified alternative methods of measuring each of the above three values and examines their use in predicting levels of *blocking* and *waiting* that arise at individual workstations. In addition, for each of these alternative methods the correct calculation formula for triangular distributions has been identified and used.

Within each workstation within a flow line this research has identified that there can exist a range of sources of variation. Each of the sources within a single workstation can possess different degrees of variability in terms of central tendency, dispersion and skewness values. This research has grouped these sources into three categories, ie cycle time variability such as arising from variability in operator task times, short stoppages such as those arising from change-overs and long stoppages that arise through equipment breakdowns.

In order to make possible the practical determination of individual workstation variability on overall flow line performance it is essential to gain an understanding of how these individual variability sources combine to form the overall cycle time variability of an individual workstation. Here the current research has extended the method of calculating 'effective cycle times' derived by Hopp and Spearman (1996) to the determination of effective shortest, most likely and longest cycle times for a triangular distribution. Initially the method developed enabled effective shortest, most likely and longest times to be established for cycle times, short stoppages and long stoppages and then the combination of these times into a single triangular probability distribution. This was achieved as follows:

Step 1: Extend the use of Hopp and Spearman's (1996) 'availability' equation to develop triangular distributions for both Short Stoppage (SSA) and Long Stoppage availabilities (LSA). The overall effect of stoppages, whether defined as short or long, is to increase the time required to complete the tasks assigned to that workstation. This extended time has been defined as the 'effective cycle time' by Hopp and Spearman (1996) who provided Equation 1 and 2 for calculating its value. Hopp and Spearman used only single values for the 'cycle time' and 'availability'. The current research extends the use of this formula to include three values for each variable, i.e. those that define the triangular distribution. As such it, therefore, enables the variance involved in these values to be included and, hence, their effect on workstation efficiency as shown in Equations 7, 8 and 9 as well as Equations 10,11,12.

Steps 2 and 3: Use the Short Stoppage 'availability' distributions resulting from Step 1 to convert task time distributions into a distribution of 'effective' task times, i.e. task times that would arise due to the occurrence of short stoppages. Use the Long Stoppage 'availability' distribution resulting from Step 1 to modify the distribution of effective task times resulting from Short Stoppages, i.e. from Step 2, to include the effect of Long Stoppages. Hence, the effective task times that would arise are those due to the occurrence of both Short and Long stoppages. The use of both long and short stoppage availabilities provides flexibility in terms of the range of operating environments the current research is applicable to. For example, if equipment maintenance operations were undertaken outside normal flow line operating periods then long stoppage availability need not be used to determine the overall effective cycle times.

Step 4: Using the effective task times resulting from Step 3 employ the PERT technique to determine total workstation effective cycle time variability arising from the variability of the individual sequential tasks allocated to a workstation.

At each of the above steps trials were carried out using computer simulation models. The results from these simulation models were compared with those resulting from the equations employed at each of the above steps. At each step the values obtained from equations were found to be in close agreement, if slightly biased in some cases in the negative direction, with those obtained from simulation models. Mean Percentage Errors ranged between -8.7% to +3.37. There appeared to be no close relationships between the levels of error produced and either frequency or duration of stoppages, i.e. correlation coefficients ranged from -0.58 to 0.62.

The methodology developed is, therefore, particularly appropriate to workstations where TAKT times are long, i.e. where they are measured in hours as opposed to seconds or minutes as on single product high volume assembly lines, since each workstation can be expected to perform a range of tasks. With the introduction of lean practices into sectors such as aerospace it can be expected that long duration TAKT flow lines will increase in popularity. In addition, when TAKT times become longer the possibility of equipment breakdowns within a TAKT cycle become more of a reality. Hence the ability to include such types of variability within the overall workstation variability will provide more realistic measures of workstation effectiveness.

Step 4 of the methodology is limited to accumulating the effects of *sequential* work tasks since it is based on the use of the PERT methodology. Within workstations, however, work tasks could well be undertaken in *parallel.* The PERT technique resolves this issue by assuming that only critical path activities are used to calculate project lead time probabilities. However warnings are always given concerning the potential of non-critical path activities becoming critical when their levels of variability are taken into consideration. Within the current work a similar assumption could, therefore, be made, i.e. that only those tasks with the greatest levels of variability are used to determine overall variability levels for a workstation.

6.4 Measuring Effects of Workstation Variability on Flow Processing Lines

It is intended to achieve the objectives of the research by making use of the workstation cycle time variability distributions to develop models by which the effects on the flow line of differences in workstation variability can be determined, i.e. the essential question to be answered was 'how do differences in levels of variability between workstations affect the levels of *blocking* and *waiting* experienced by individual workstations along the flow line?' Once the levels of blocking and waiting can be calculated for each workstation along a flow line then simple rules can be developed to:

i. Aid the allocation of tasks to workstations to improve the line balancing process, e.g.: if WS_i experiences high levels of blocking then remove tasks from WS_{i+1} and allocate to WS_i; if WS_{i+1} experiences high levels of waiting then remove tasks from WS_i and allocate to WS_{i+1}.
ii. Aid the allocation of flexible labour to workstations e.g.: if WS_i experiences high levels of blocking then move operators from this workstation to WS_{i+1} in order to reduce the effective cycle time of this workstation; if WS_{i+1} experiences high levels of waiting then move operators from this workstation to WS_i again to decrease effective cycle time.

This work initially involved categorising individual levels of variability in order to assist in identification of the types of relationships that exist between workstations. Here two methods were used, i.e.:

i. Using the shortest, most likely and longest times of the probability distribution to categorise the various shapes that triangular variability distributions could acquire i.e. Figure 4.12.

ii. Using the relative values of the shortest and longest times for successive workstations, i.e. where the eleven relationships shown in Figure 4.13 were identified.

Experiments were undertaken using the full range of distributions shown in Figures 5.7 to 5.12 in order to minimise the limitations in scope of application of any subsequent relationships found and models developed.

A range of simulation trials were then carried out in order to both identify the factors affecting the amounts of blocking and waiting occurring at individual workstations and in order to quantify the effects of these factors. The trials undertaken were designed to identify the effects of:

i. Both equal levels and differing levels of variability between workstations. In practice it would be difficult to allocate tasks to workstations such that both the mean cycle times and the variability in these cycle times were identical at each workstation along the line. However, the use of such lines prevented the effects caused by differences in the variability between workstations from obscuring the effects of workstation position, level of variability and flow line length.

ii. Number of workstations within a flow line and position of a workstation within a flow line. Although previous research has examined flow lines of different lengths no explicit analyses have been carried out to quantitatively identify the effect line length and workstation position have on the utilisation of individual workstations.

In addition the trials were intended to identify where applicable the relationships of statistical measures such as the mean, standard deviation and coefficient of variation to levels of workstation blocking and waiting. Several researchers have successfully developed mathematical models that relate coefficient of variation with the overall throughput rate of flow lines. However, there are no models available in the research literature that make use of statistical measures to calculate the levels of blocking and waiting that occur at individual workstations.

The results indicated that, where common levels of workstation variability existed, the following basic rules held at all levels of workstation variability, i.e.:

i. The % Blocking at the 1st workstation was approximately equal to the % Waiting at the last workstation in the line. This is in agreement with the findings of Slack and Wild (1972) although this research focussed on one specific flow processing line and did not indicate the general nature of this result, i.e. it applies to all workstations possessing common levels of variability between workstations.

ii. The value of the maximum level of %Blocking, and hence %Waiting, is related both to the level of variability exhibited by workstations and the number of workstations within the flow line.

iii. The %Blocking was at its maximum at the 1st workstation and gradually decreased at each subsequent workstation until becoming zero at the last workstation. It is assumed that items can always exit instantaneously from the last workstation and hence no blocking occurs at this work area. The rate at which this decrease in % Blocking occurs is greater between workstations at the start and end of the flow line then between those workstations in the centre of the line, i.e. rate of decrease is non-linear. The current research has divided this non-linear decrease in % Blocking into three linear sections for the purposes of developing estimating equations. Although this introduces some degree of inaccuracy into the resulting estimates it is assumed that this is not sufficient to invalidate any implementation plans for dealing with the effects of this variability, e.g. in terms of plans for flexing labour between workstations.

iv. The %Waiting was zero at the 1st workstation and gradually increased at each subsequent workstation until reaching its maximum at the last workstation. It is assumed there is no waiting for items to be transferred to the 1st workstation, i.e. instantaneous replenishment. The rate at which this increase in % Waiting occurs is greater between workstations at the start and end of the flow line then between those workstations in the centre of the line, i.e. rate of increase is non-linear.

v. The sum of the %Blocking and %Waiting were approximately equal at all workstations along the line. Since the % Waiting at the first workstation is zero then the sum of the % Blocking and % Waiting at all subsequent workstations is equal to the % Blocking at the first workstation. Hence, from knowledge of the % Blocking at each workstation the % Waiting can be easily inferred. The current research, therefore, makes use of this by focussing on the development of models for estimating % Blocking only at workstations.

Figure 5.17 provides the levels of blocking and waiting that arise within 2-workstation flow lines. Hence, the relative effects on blocking and waiting of 'number of workstations within a flow line' and 'the position of a workstation within the flow line' are effectively removed from these results. Analysis of these results has been undertaken to identify the basic factors that determine the levels of blocking and waiting arising at specific workstations.

From examination of these results the following observations have been made, i.e.:

i. Where workstations possess common levels of variability two basic factors are observed to determine the relative amounts of blocking and, hence, waiting that arise, i.e. central tendency and the level of dispersion of the probability distribution. The ratio of these two values is directly correlated to the amount of blocking that arises.

ii. It is differences in levels of variability between successive workstations that causes the greatest differences in the relative amounts of blocking at the preceding workstation and waiting at the succeeding workstation. Where common levels of variability exist between workstations the tendency is for % Blocking levels to decrease as the central tendency of the probability distribution increases. However, the reverse occurs when mixed levels of variability exist, i.e. % Blocking levels increase as the central tendency of the probability distribution increases.

iii. The relationships between A, B, C and D, i.e. as shown in Figure 4.13, do not necessarily determine the basic relationships between levels of blocking at the preceding workstation and waiting at the succeeding workstation. However, some of the eleven relationships are consistent in their relationship to levels of blocking and waiting. With other relationships, however, the relative effects depend on the actual differences in variability between the two workstations.

The results indicated that, where mixed levels of workstation variability existed on multi-station flow lines, then identifying common patterns of %Blocking and %Waiting was difficult. Examination of the correlation between the values of the various statistical measures, i.e. means, geometric means, harmonic means, PERT means, standard deviations, coefficient of variations and the medians of the workstation cycle time variability, and the actual %Blocking and %Waiting that occurred indicated that no one measure was highly correlated with these results.

These results also indicated that at the workstations preceding and succeeding the workstation with differing variability the relative amounts of %Blocking and %Waiting were disturbed. No common cause was obvious from examination of the results to account for the way in which this disturbance occurred. The probable causes influencing the relative amounts of disturbance could not be visually identified although line length did appear not to affect these values. A variety of trials were undertaken in an attempt to identify the factors effecting levels of blocking and waiting. The following observations arose from these trials.

i. $\%B_{i,n} = f(i, n, V_i - V_{i+1})$ and $\%W_{i,n} = f(i, n, V_{i+1} - V_i)$ where V represents the level of variability.

ii. $\%B_{i,n}$ levels are also effected by $\%B_{i+1,n}$ ..... $\%B_{n-1,n}$ levels with the effect decreasing as i increases.

iii. $\%W_{i,n}$ levels are also effected by $\%W_{i-1,n}$ ..... $\%W_{1,n}$ levels with the effect decreasing as i decreases.

iv. No statistical measures of variability, including i.e. mean, median, standard deviation or coefficient of variation, seem to be strongly related to the effects this variability has on levels of blocking and waiting.

v. Both the levels of dispersion and central value of the workstation variability affect the levels of blocking and waiting that occur. Where equal amounts of variability are present the workstation with the greatest central value will have the greatest effect on blocking levels.

vi. The relative values of A, B, C and D, (Figure 4.12), effect whether blocking, waiting or both occur and the relative levels of blocking and waiting that occur. However, these relative effects appear not to be present in all cases where there are mixed variability workstations. In addition, the values of the areas under the probability distributions that are responsible for blocking and waiting do not always appear to be related to the levels of blocking and waiting that occur.

vii. Differences in levels of variability between workstations can be responsible for causing the greatest levels of blocking and waiting on workstations preceding or succeeding them. This effect is difficult to predict since it also depends on the relative values of A, B, C and D.

Overall it can be assumed, therefore, that the rules governing the interactions that effect blocking and waiting on a mixed variability flow processing line are sufficiently complex to require some form of rule base in order to provide a suitable method of estimation.

6.5 Improving the Design and Operation of Flow Processing Lines

It is argued that the current research, through its development of models for estimating the levels of blocking and waiting occurring at individual workstations, will contribute to the improvement in the design and operation of flow processing lines containing high levels of variability. These improvements will arise from using knowledge of levels of blocking and waiting arising at individual workstations to enable more effective use of the available methods for dealing with the effects of variability as follows:

i. Improved **line balancing** through use of the knowledge of blocking and waiting levels to allocate tasks to workstations such that one or more of the following objectives are achieved, i.e.: balanced levels of blocking and waiting at each workstation; causes of high levels of blocking and waiting limited to specific workstations to facilitate improvement through continuous improvement exercises and/or to simplify and improve flexible labour planning; avoidance of high levels of blocking and waiting occurring at workstations that contain 'scarce' resources hence ensuring effective utilisation of these resources.

ii. **Removing causes and reducing levels of variability** through focussing improvement resources and activities to those workstations that are the cause of high levels of blocking and waiting.

iii. Improved **variability buffering** through provision of suitable material buffers feeding workstations that have high levels of waiting, reduction of buffers feeding workstations with high levels of blocking, and/or providing buffers after workstations with high levels of blocking.

iv. Improved use of **flexible labour** through using a knowledge of the blocking and waiting levels arising at individual workstations to plan levels of labour flexibility required and develop suitable training matrices for providing these levels of flexibility. In addition improved control of the movement of labour during operation of the flow line could be gained by moving operators from an upstream workstation with high levels of waiting to a downstream workstation that possesses high levels of utilisation, by moving operators from a downstream workstation with high levels of blocking to an upstream workstation that possesses high levels of utilisation, and by avoiding the movement of operators between workstations that both possess high levels of blocking and/or waiting.

v. Improved **sequencing of work items onto the flow line** through development of appropriate production schedules for workstations causing high levels of blocking and waiting, i.e. these schedules would need to minimise levels of variability, for example by reducing the number of set-ups, and/or help to restrict the occurrence of high levels of variability to those work periods in which they can be better dealt with.

Chapter 7 Conclusions

Greater levels of product and process variability are rapidly becoming an inherent part of the environment under which flow processing lines must operate. The overall effect of this variability is to drastically reduce flow process line efficiency leading to reduced throughput rates and inefficient use of labour and equipment resources.

The aim of the current research is to enable high variability flow lines to operate more effectively through enabling the improved use of methods that can help to overcome the detrimental effects of this variability. At the same time, to improve the use of made of line balancing, part sequencing continuous improvement, resource pooling and flexible labour to increase the effectiveness of flow processing lines. The improved use of these techniques required knowledge of individual work tasks, the levels of variability of individual workstations and the effects that differences in workstation variability have on individual workstation utilisation.

The **objectives of the research** have, therefore, focused on the development of methods by which this information can be gained and have achieved the following:

Main Task 1: Development of a method for combining the individual elements of variability that arise within a workstation into a single variability probability distribution.

Main Task 2: Development of a method for estimating the effects on a flow line of differences in the levels of variability between workstations.

Achieving these research objectives focuses on the need to develop methods for quantitatively measuring the levels of *blocking* and *waiting* that arise within individual workstations as a result of variability.

i. **Novel mathematical models,** (Equations 22 and 23)**, have been developed for quantitatively estimating the levels of blocking and waiting arising at individual workstations as a result of the effects of workstation cycle time variability.** The novelty of these models lies in their ability to quantitatively estimate both % Blocking and % Waiting levels for individual workstations within a flow processing line. The models make use of *workstation position* in the flow line, line length in terms of the *number of workstations*, and the levels of *cycle time variability* exhibited by workstations as model variables.

   The models developed are capable of estimating the %Blocking and the %Waiting levels arising on flow processing lines up to 21 workstations in length where there are common levels of variability between each workstation. The accuracy of the estimates generated by the model, when compared with results obtained from simulation experiments, are in the range -0.46 and +0.38.

1. **A method of more precisely defining individual sources of variability has been developed.** This definition uses information concerning the *time when the event*

occurs that causes the variation, the *length of time that the event causing the variation occurs over*, and the *level of variation caused by the event.* For each of these factors information is then required concerning their *predictability*, *whether their cause is known* and whether *methods are available for controlling them.* The method developed, when compared with existing methods of defining causes of variability, provides improved direction for undertaking activities aimed at removing sources of variation or reducing the effects of this variation. (Section 3.2.2)

2. **A method has been developed, (i.e. Equations 7 to 21), for combining the variability arising from various sources within an individual workstation into a single variability probability distribution for that workstation.** This method is a radical extension of an existing method in that it makes use of triangular probability distributions to represent the *task times for an individual task within a workstation*, the *resulting availability of a workstation to perform useful work due to the occurrence of short stoppages,* (e.g. such as set-ups), and the *resulting availability of a workstation to perform useful work due to the occurrence of long stoppages*, (e.g. such as equipment breakdowns). The method then uses these triangular probability distributions to develop a triangular probability distribution for the variability in *effective task cycle times* resulting from the occurrence of both long and short stoppages.

The resulting accuracy of the effective cycle time distributions are high when compared with distributions developed using discrete event simulation, i.e. Mean Percentage Errors range between -0.35% to +0.11%. (Section 5.2)

3. **The effects of mixed levels of workstation cycle time variability on the levels of blocking and waiting occurring on individual workstations have been identified using simulation experiments,** i.e. where a wide variety of variability levels exists between workstations and there are sudden large changes in variability levels between adjacent workstations. From analysis of experimental results it was concluded that the rules governing the interactions between individual workstation blocking and waiting levels on a mixed variability flow processing line are sufficiently complex to require some form of rule base in order to provide a suitable method of estimation.

7. Recommendations for Further Work

The following recommendations for further work have been identified:

1. Further work needs to be undertaken with respect to the development of methods by which %Blocking and %Waiting of individual workstations can be estimated when mixed levels of variability exist between workstations. As argued this is likely to require the development of a 'rule based' methodology. Important questions to resolve would include identifying the effect on % Blocking and % Waiting of individual workstations of:

   i. The variability categories illustrated in Figure 4.13.

   ii. The levels of variability exhibited by workstations, i.e. as illustrated in Figure 4.12.

   iii. The values of the areas under the triangular probability distribution that result in blocking, waiting or both, i.e. as illustrated in Figure 4.13.

   iv. The distance between workstations, i.e. in terms of the number of workstations.

v. The levels of blocking and waiting that occur in 2 workstation flow lines, i.e. Figure 5.17

2. The models developed for estimating workstation %Blocking and %Waiting when common levels of variability exist between workstations are essentially linear in nature whereas the actual relationships can be seen, (i.e. as in Figures 5.7 to 5.12), to be non-linear. Hence, further work would be required to establish models that better represent the true nature of this non-linear relationship.

3. The method developed for more precisely defining individual sources of variability needs further testing by its use to identify and resolve practical variability issues.

4. Probability distribution types, other then triangular, could be considered for use within the methodology. For example the *beta* distribution is flexible in its ability to approximate a wide range of distribution types.

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Appendix – Basic Simulation Results for Figure 5.1

a	t	b	WS Position	% $B_{1,2}$	Actual % $B_{1,n}$	Actual % $W_{1,n}$
3	3	4	1	3.86	3.86	0.00
3	3	4	2		0.00	3.83
3	3	4	1	3.86	5.51	0.00
3	3	4	2	3.86	3.06	2.45
3	3	4	3		0.00	5.48
3	3	4	1	3.86	6.96	0.00
3	3	4	2	3.86	5.29	1.72
3	3	4	3	3.86	4.07	2.90
3	3	4	4	3.86	2.61	4.39
3	3	4	5		0.00	6.91
3	3	4	1	3.86	7.88	0.00
3	3	4	2	3.86	5.53	2.23
3	3	4	3	3.86	5.23	2.58
3	3	4	4	3.86	4.93	2.86
3	3	4	5	3.86	4.13	3.70
3	3	4	6	3.86	3.43	4.43
3	3	4	7	3.86	2.22	5.74
3	3	4	8		0.00	7.87
3	3	4	1	3.86	8.19	0.00
3	3	4	2	3.86	7.21	0.98
3	3	4	3	3.86	6.43	1.78
3	3	4	4	3.86	5.86	2.34
3	3	4	5	3.86	5.54	2.64
3	3	4	6	3.86	5.08	3.12
3	3	4	7		4.84	3.33
3	3	4	8	3.86	4.75	3.54
3	3	4	9	3.86	4.43	3.79
3	3	4	10	3.86	3.80	4.37
3	3	4	11	3.86	3.22	5.05
3	3	4	12	3.86	2.14	6.11
3	3	4	13		0.00	8.17
3	3	4	1	3.86	8.49	0.00
3	3	4	2	3.86	7.61	0.78
3	3	4	3	3.86	7.03	1.35
3	3	4	4	3.86	6.66	1.79
3	3	4	5	3.86	6.58	1.86
3	3	4	6	3.86	6.30	2.15
3	3	4	7	3.86	5.99	2.45
3	3	4	8	3.86	5.91	2.55
3	3	4	9	3.86	5.89	2.58
3	3	4	10	3.86	5.71	2.78
3	3	4	11	3.86	5.67	2.83
3	3	4	12	3.86	5.48	2.94
3	3	4	13	3.86	5.32	3.12
3	3	4	14	3.86	5.28	3.17
3	3	4	15	3.86	4.92	3.45
3	3	4	16	3.86	4.60	3.72
3	3	4	17	3.86	4.30	4.08
3	3	4	18	3.86	3.87	4.58
3	3	4	19	3.86	3.35	5.08
3	3	4	20	3.86	2.30	6.07
3	3	4	21		0.00	8.42

Basic Simulation Results for Figure 5.2

a	t	b	WS Position	% $B_{1,2}$	Simulation %Blocking Results	Simulation %Waiting Results
0	3	6	1	19.1	19.10	0.00
0	3	6	2		0.00	19.08
0	3	6	1	19.10	24.70	0.00
0	3	6	2	19.10	14.43	10.45
0	3	6	3		0.00	24.60
0	3	6	1	19.10	28.91	0.00
0	3	6	2	19.10	22.58	6.75
0	3	6	3	19.10	17.87	11.46
0	3	6	4	19.10	11.94	17.23
0	3	6	5		0.00	28.65
0	3	6	1	19.10	30.96	0.00
0	3	6	2	19.10	25.81	5.32
0	3	6	3	19.10	23.26	7.99
0	3	6	4	19.10	21.13	10.48
0	3	6	5	19.10	17.81	13.95
0	3	6	6	19.10	14.89	17.21
0	3	6	7	19.10	10.07	21.22
0	3	6	8		0.00	31.00
0	3	6	1	19.10	28.52	0.00
0	3	6	2	19.10	25.47	3.87
0	3	6	3	19.10	23.28	4.89
0	3	6	4	19.10	21.99	6.34
0	3	6	5	19.10	20.60	7.89
0	3	6	6	19.10	19.91	8.66
0	3	6	7	19.10	19.68	8.89
0	3	6	8	19.10	18.52	9.88
0	3	6	9	19.10	16.09	12.33
0	3	6	10	19.10	13.84	14.66
0	3	6	11	19.10	9.57	18.87
0	3	6	12	19.10	4.32	23.99
0	3	6	13		0.00	28.48
0	3	6	1	19.10	32.60	0.00
0	3	6	2	19.10	29.40	3.54
0	3	6	3	19.10	27.55	5.27
0	3	6	4	19.10	26.18	6.54
0	3	6	5	19.10	25.86	7.03
0	3	6	6	19.10	24.87	7.88
0	3	6	7	19.10	23.87	8.98
0	3	6	8	19.10	23.33	9.35
0	3	6	9	19.10	22.85	10.03
0	3	6	10	19.10	22.65	10.23
0	3	6	11	19.10	22.48	10.44
0	3	6	12	19.10	22.08	10.88
0	3	6	13	19.10	21.59	11.13
0	3	6	14	19.10	21.29	11.55
0	3	6	15	19.10	20.05	12.89
0	3	6	16	19.10	18.98	13.99
0	3	6	17	19.10	17.93	14.99
0	3	6	18	19.10	16.26	16.68
0	3	6	19	19.10	13.89	18.88
0	3	6	20	19.10	10.28	22.55
0	3	6	21		0.00	32.55

Basic Simulation Results for Figure 5.3

WS1-WS10			WS1		WS2		WS3		WS4		WS5		WS6	
a	t	b	%Waiting	%Blocking	%Waiting	%Blocking	%Waiting	%Blocking	%Waiting	%Blocking	%Waiting	%Blocking	%Waiting	%Blocking
2	3	4	0.04	13.07	1.83	11.21	2.99	10.44	4.06	9.80	4.43	8.69	5.95	7.91
1	3	5	0.04	23.02	3.04	19.69	5.27	18.21	6.91	16.92	7.83	15.01	10.47	13.51
0	3	6	0.04	30.94	3.91	26.62	6.98	25.22	8.70	23.28	9.50	21.03	12.76	18.26
5	6	7	0.04	7.01	1.17	6.10	2.10	5.35	3.00	5.16	3.01	4.76	4.11	4.09
4	6	8	0.04	12.85	2.00	11.49	3.47	10.13	4.64	9.51	4.85	8.70	6.54	7.61
3	6	9	0.04	17.81	2.80	16.19	4.81	14.91	6.28	13.33	6.54	12.27	8.88	10.50
2	3	6	0.04	21.42	2.92	18.56	4.86	16.92	6.60	15.82	7.12	13.95	9.75	11.75
0	3	5	0.04	29.01	3.55	25.01	6.17	23.43	8.23	21.62	9.09	19.33	12.42	17.71
1	3	6	0.04	26.12	3.35	22.57	5.58	20.99	7.50	19.40	8.18	17.20	11.23	14.86

WS7		WS8		WS9		WS10	
%Waiting	%Blocking	%Waiting	%Blocking	%Blocking	%Blocking	%Waiting	%Blocking
6.63	7.58	7.91	6.38	9.25	4.34	14.32	0.00
11.46	13.28	13.22	11.22	15.55	7.72	24.36	0.00
15.43	18.13	15.12	17.31	20.28	10.52	31.44	0.00
4.83	4.28	5.56	3.55	6.33	2.39	9.19	0.00
7.60	8.33	8.61	6.39	10.22	4.39	14.98	0.00
10.19	11.23	11.73	8.88	13.80	6.03	20.07	0.00
11.79	11.81	13.02	9.90	14.78	6.96	21.95	0.00
13.39	17.50	15.75	14.53	18.89	9.92	30.51	0.00
11.23	14.87	13.67	14.87	15.10	12.34	26.61	0.00

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Basic Simulation Results for Figure 5.7

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
3	3	4	1	3.86	3.86	0.00
3	3	4	2		0.00	3.25
2	3	3	1	4.8	4.80	0.00
2	3	3	2		0.00	4.74
3	3	5	1	6.83	6.83	0.00
3	3	5	2		0.00	6.73
2	3	4	1	7.11	7.26	0.00
2	3	4	2		0.00	7.07
3	3	6	1	9.18	9.18	0.00
3	3	6	2		0.00	9.04
2	3	5	1	9.72	9.72	0.00
2	3	5	2		0.00	9.59
1	3	3	1	10.29	10.29	0.00
1	3	3	2		0.00	10.25
1	3	4	1	11.84	11.84	0.00
1	3	4	2		0.00	11.74
2	3	6	1	11.75	11.75	0.00
2	3	6	2		0.00	11.59
1	3	5	1	13.55	13.55	0.00
1	3	5	2		0.00	13.43
1	3	6	1	15.09	15.09	0.00
1	3	6	2		0.00	14.91
0	3	3	1	16.58	16.74	0.00
0	3	3	2		0.00	16.68
0	3	4	1	16.52	17.29	0.00
0	3	4	2		0.00	17.72
0	3	5	1	18.33	18.17	0.00
0	3	5	2		0.00	17.67
0	3	6	1	19.1	19.10	0.00
0	3	6	2		0.00	18.87

Basic Simulation Results for Figure 5.8

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
3	3	4	1	3.86	5.51	0.00
3	3	4	2	3.86	3.06	2.88
3	3	4	3		0.00	5.45
2	3	3	1	4.80	6.31	0.00
2	3	3	2	4.80	3.90	3.50
2	3	3	3		0.00	5.98
3	3	5	1	6.83	9.58	0.00
3	3	5	2	6.83	5.31	5.31
3	3	5	3		0.00	9.30
2	3	4	1	7.11	9.83	0.00
2	3	4	2	7.11	5.72	4.98
2	3	4	3		0.00	9.45
3	3	6	1	9.18	12.69	0.00
3	3	6	2	9.18	7.04	6.40
3	3	6	3		0.00	12.55
2	3	5	1	9.72	13.25	0.00
2	3	5	2	9.72	7.55	6.98
2	3	5	3		0.00	13.15
1	3	3	1	10.29	13.33	0.00
1	3	3	2	10.29	8.26	8.26
1	3	3	3		0.00	12.98
1	3	4	1	11.84	15.50	0.00
1	3	4	2	11.84	9.28	8.45
1	3	4	3		0.00	15.20
2	3	6	1	11.75	15.97	0.00
2	3	6	2	11.75	8.97	8.97
2	3	6	3		0.00	14.88
1	3	5	1	13.55	17.94	0.00
1	3	5	2	13.55	10.47	9.25
1	3	5	3		0.00	17.45
1	3	6	1	15.09	20.00	0.00
1	3	6	2	15.09	11.50	11.50
1	3	6	3		0.00	19.88
0	3	3	1	16.58	21.23	0.00
0	3	3	2	16.58	13.17	12.45
0	3	3	3		0.00	21.04
0	3	4	1	16.52	22.05	0.00
0	3	4	2	16.52	13.38	12.55
0	3	4	3		0.00	21.98
0	3	5	1	18.33	23.41	0.00
0	3	5	2	18.33	13.91	12.24
0	3	5	3		0.00	23.12
0	3	6	1	19.10	24.70	0.00
0	3	6	2	19.10	14.43	8.95
0	3	6	3		0.00	24.45

Basic Simulation Results for Figure 5.9

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
3	3	4	1	3.86	6.96	0.00
3	3	4	2	3.86	5.29	2.44
3	3	4	3	3.86	4.07	3.85
3	3	4	4	3.86	2.61	4.87
3	3	4	5		0.00	6.55
2	3	3	1	4.80	7.44	0.00
2	3	3	2	4.80	6.14	2.98
2	3	3	3	4.80	4.93	4.50
2	3	3	4	4.80	3.46	6.28
2	3	3	5		0.00	7.04
3	3	5	1	6.83	11.93	0.00
3	3	5	2	6.83	9.07	3.45
3	3	5	3	6.83	7.01	6.78
3	3	5	4	6.83	4.47	8.88
3	3	5	5		0.00	11.78
2	3	4	1	7.11	11.95	0.00
2	3	4	2	7.11	9.34	3.98
2	3	4	3	7.11	7.34	6.45
2	3	4	4	7.11	4.93	8.88
2	3	4	5		0.00	11.44
3	3	6	1	9.18	15.70	0.00
3	3	6	2	9.18	11.97	4.88
3	3	6	3	9.18	9.25	8.45
3	3	6	4	9.18	5.91	10.25
3	3	6	5		0.00	15.45
2	3	5	1	9.72	16.15	0.00
2	3	5	2	9.72	12.43	5.40
2	3	5	3	9.72	9.69	8.44
2	3	5	4	9.72	6.33	11.45
2	3	5	5		0.00	15.88
1	3	3	1	10.29	15.56	0.00
1	3	3	2	10.29	12.83	6.44
1	3	3	3	10.29	10.41	9.48
1	3	3	4	10.29	7.20	11.25
1	3	3	5		0.00	15.22
1	3	4	1	11.84	18.27	0.00
1	3	4	2	11.84	14.61	6.55
1	3	4	3	11.84	11.66	10.10
1	3	4	4	11.84	7.99	13.88
1	3	4	5		0.00	18.11

Basic Simulation Results for Figure 5.9 – cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
2	3	6	1	11.75	19.43	0.00
2	3	6	2	11.75	14.84	6.40
2	3	6	3	11.75	11.59	10.82
2	3	6	4	11.75	7.46	13.25
2	3	6	5		0.00	19.11
1	3	5	1	13.55	21.37	0.00
1	3	5	2	13.55	16.72	7.14
1	3	5	3	13.55	13.15	12.45
1	3	5	4	13.55	8.79	15.77
1	3	5	5		0.00	21.08
1	3	6	1	15.09	23.87	0.00
1	3	6	2	15.09	18.43	8.40
1	3	6	3	15.09	14.50	13.78
1	3	6	4	15.09	9.53	17.55
1	3	6	5		0.00	23.44
0	3	3	1	16.58	24.33	0.00
0	3	3	2	16.58	20.16	8.21
0	3	3	3	16.58	16.30	10.21
0	3	3	4	16.58	11.27	11.27
0	3	3	5		0.00	24.04
0	3	4	1	16.52	24.49	0.00
0	3	4	2	16.52	20.63	10.25
0	3	4	3	16.52	16.62	14.25
0	3	4	4	16.52	11.40	18.24
0	3	4	5		0.00	23.89
0	3	5	1	18.33	27.36	0.00
0	3	5	2	18.33	21.62	9.12
0	3	5	3	18.33	17.15	14.52
0	3	5	4	18.33	11.64	18.87
0	3	5	5		0.00	27.12
0	3	6	1	19.10	28.91	0.00
0	3	6	2	19.10	22.58	10.85
0	3	6	3	19.10	17.87	15.28
0	3	6	4	19.10	11.94	21.25
0	3	6	5		0.00	28.55

Basic Simulation Results for Figure 5.10

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
3	3	4	1	3.86	7.54	0.00
3	3	4	2	3.86	5.53	1.98
3	3	4	3	3.86	5.23	2.14
3	3	4	4	3.86	4.93	3.45
3	3	4	5	3.86	4.13	4.02
3	3	4	6	3.86	3.43	4.98
3	3	4	7	3.86	2.22	5.14
3	3	4	8		0.00	7.49
2	3	3	1	4.80	7.74	0.00
2	3	3	2	4.80	7.05	1.98
2	3	3	3	4.80	6.34	2.87
2	3	3	4	4.80	5.82	3.25
2	3	3	5	4.80	5.12	3.55
2	3	3	6	4.80	4.72	4.25
2	3	3	7	4.80	3.16	6.21
2	3	3	8		0.00	7.54
3	3	5	1	6.83	12.76	0.00
3	3	5	2	6.83	10.90	3.50
3	3	5	3	6.83	9.65	4.77
3	3	5	4	6.83	8.68	5.45
3	3	5	5	6.83	7.52	6.98
3	3	5	6	6.83	6.49	7.58
3	3	5	7	6.83	3.93	8.98
3	3	5	8		0.00	12.66
2	3	4	1	7.11	13.22	0.00
2	3	4	2	7.11	11.48	4.12
2	3	4	3	7.11	10.36	6.58
2	3	4	4	7.11	9.32	7.54
2	3	4	5	7.11	8.39	8.88
2	3	4	6	7.11	7.06	9.15
2	3	4	7	7.11	5.39	10.98
2	3	4	8		0.00	13.10

Basic Simulation Results for Figure 5.10- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
3	3	6	1	9.18	17.34	0.00
3	3	6	2	9.18	14.88	5.48
3	3	6	3	9.18	13.31	8.78
3	3	6	4	9.18	11.96	9.45
3	3	6	5	9.18	10.56	10.88
3	3	6	6	9.18	9.14	13.24
3	3	6	7	9.18	6.48	14.65
3	3	6	8		0.00	17.15
2	3	5	1	9.72	17.28	0.00
2	3	5	2	9.72	14.64	4.65
2	3	5	3	9.72	12.92	8.41
2	3	5	4	9.72	11.82	9.45
2	3	5	5	9.72	10.70	10.14
2	3	5	6	9.72	9.08	11.48
2	3	5	7	9.72	5.72	13.45
2	3	5	8		0.00	17.25
1	3	3	1	10.29	16.73	0.00
1	3	3	2	10.29	15.18	5.98
1	3	3	3	10.29	14.19	8.14
1	3	3	4	10.29	12.75	10.78
1	3	3	5	10.29	11.40	12.25
1	3	3	6	10.29	9.91	13.24
1	3	3	7	10.29	7.92	14.24
1	3	3	8		0.00	16.45
1	3	4	1	11.84	19.95	0.00
1	3	4	2	11.84	17.01	6.12
1	3	4	3	11.84	15.24	8.45
1	3	4	4	11.84	13.98	10.28
1	3	4	5	11.84	12.81	11.87
1	3	4	6	11.84	10.92	13.44
1	3	4	7	11.84	7.32	15.25
1	3	4	8		0.00	19.78

Basic Simulation Results for Figure 5.10- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
2	3	6	1	11.75	21.11	0.00
2	3	6	2	11.75	17.35	4.65
2	3	6	3	11.75	15.35	8.74
2	3	6	4	11.75	14.04	9.87
2	3	6	5	11.75	12.81	12.09
2	3	6	6	11.75	11.10	14.25
2	3	6	7	11.75	6.81	16.45
2	3	6	8		0.00	20.99
1	3	5	1	13.55	23.37	0.00
1	3	5	2	13.55	20.16	0.00
1	3	5	3	13.55	17.96	7.41
1	3	5	4	13.55	16.58	10.54
1	3	5	5	13.55	14.80	12.47
1	3	5	6	13.55	12.53	15.47
1	3	5	7	13.55	9.41	18.98
1	3	5	8		0.00	23.01
1	3	6	1	15.09	25.99	0.00
1	3	6	2	15.09	21.50	6.78
1	3	6	3	15.09	18.96	12.01
1	3	6	4	15.09	17.33	13.27
1	3	6	5	15.09	15.91	15.98
1	3	6	6	15.09	13.81	16.41
1	3	6	7	15.09	8.64	19.47
1	3	6	8		0.00	25.68
0	3	3	1	16.58	25.92	0.00
0	3	3	2	16.58	23.62	10.25
0	3	3	3	16.58	22.15	14.55
0	3	3	4	16.58	19.85	16.47
0	3	3	5	16.58	17.77	18.75
0	3	3	6	16.58	15.44	21.40
0	3	3	7	16.58	12.33	22.45
0	3	3	8		0.00	25.88

Basic Simulation Results for Figure 5.10- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
0	3	4	1	16.52	27.34	0.00
0	3	4	2	16.52	23.52	9.22
0	3	4	3	16.52	21.16	13.12
0	3	4	4	16.52	19.51	17.88
0	3	4	5	16.52	18.12	19.14
0	3	4	6	16.52	15.43	20.14
0	3	4	7	16.52	10.47	22.14
0	3	4	8		0.00	27.22
0	3	5	1	18.33	28.32	0.00
0	3	5	2	18.33	24.99	8.50
0	3	5	3	18.33	22.14	14.35
0	3	5	4	18.33	20.01	15.25
0	3	5	5	18.33	17.55	18.45
0	3	5	6	18.33	15.99	21.01
0	3	5	7	18.33	10.14	23.78
0	3	5	8		0.00	28.01
0	3	6	1	19.10	30.96	0.00
0	3	6	2	19.10	25.81	8.98
0	3	6	3	19.10	23.26	12.24
0	3	6	4	19.10	21.13	16.54
0	3	6	5	19.10	17.81	18.78
0	3	6	6	19.10	14.89	21.25
0	3	6	7	19.10	10.07	23.58
0	3	6	8		0.00	30.86

Basic Simulation Results for Figure 5.11

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
3	3	4	1	3.86	8.19	0.00
3	3	4	2	3.86	7.21	1.98
3	3	4	3	3.86	6.43	2.98
3	3	4	4	3.86	5.86	3.65
3	3	4	5	3.86	5.54	3.70
3	3	4	6	3.86	5.08	4.33
3	3	4	7	3.86	4.84	4.55
3	3	4	8	3.86	4.75	4.55
3	3	4	9	3.86	4.43	4.98
3	3	4	10	3.86	3.80	5.48
3	3	4	11	3.86	3.22	5.65
3	3	4	12	3.86	2.14	6.98
3	3	4	13		0.00	8.14
2	3	3	1	4.80	8.16	0.00
2	3	3	2	4.80	7.50	2.40
2	3	3	3	4.80	7.22	2.97
2	3	3	4	4.80	7.07	3.14
2	3	3	5	4.80	6.67	3.25
2	3	3	6	4.80	6.57	4.25
2	3	3	7	4.80	6.51	4.99
2	3	3	8	4.80	6.45	5.45
2	3	3	9	4.80	5.67	5.78
2	3	3	10	4.80	5.10	6.35
2	3	3	11	4.80	4.66	6.45
2	3	3	12	4.80	3.66	6.88
2	3	3	13		0.00	8.04
3	3	5	1	6.83	14.06	0.00
3	3	5	2	6.83	12.31	2.54
3	3	5	3	6.83	11.29	3.95
3	3	5	4	6.83	10.81	4.47
3	3	5	5	6.83	10.10	5.65
3	3	5	6	6.83	9.88	7.88
3	3	5	7	6.83	9.44	8.32
3	3	5	8	6.83	9.29	8.47
3	3	5	9	6.83	8.33	9.88
3	3	5	10	6.83	7.11	10.05
3	3	5	11	6.83	6.18	10.25
3	3	5	12	6.83	4.06	11.98
3	3	5	13		0.00	13.88

Basic Simulation Results for Figure 5.11- cont'd

a	t	b	WS Position	% B_{12}	Individual Workstation %Blocking	Individual Workstation %Waiting
2	3	4	1	7.11	13.79	0.00
2	3	4	2	7.11	12.25	4.01
2	3	4	3	7.11	11.50	4.25
2	3	4	4	7.11	10.67	6.98
2	3	4	5	7.11	9.67	7.54
2	3	4	6	7.11	9.26	8.12
2	3	4	7	7.11	8.92	8.36
2	3	4	8	7.11	8.48	8.54
2	3	4	9	7.11	8.27	9.25
2	3	4	10	7.11	7.31	9.88
2	3	4	11	7.11	6.07	11.25
2	3	4	12	7.11	4.21	11.98
2	3	4	13		0.00	13.55
3	3	6	1	9.18	18.50	0.00
3	3	6	2	9.18	16.19	4.25
3	3	6	3	9.18	14.90	5.55
3	3	6	4	9.18	13.88	6.45
3	3	6	5	9.18	12.69	9.65
3	3	6	6	9.18	11.86	10.05
3	3	6	7	9.18	11.57	10.25
3	3	6	8	9.18	11.13	10.88
3	3	6	9	9.18	10.61	11.88
3	3	6	10	9.18	9.08	12.77
3	3	6	11	9.18	7.50	13.55
3	3	6	12	9.18	5.07	15.88
3	3	6	13		0.00	18.36
2	3	5	1	9.72	19.13	0.00
2	3	5	2	9.72	17.00	4.65
2	3	5	3	9.72	16.08	6.25
2	3	5	4	9.72	14.52	7.88
2	3	5	5	9.72	13.68	9.98
2	3	5	6	9.72	12.86	10.22
2	3	5	7	9.72	12.26	11.15
2	3	5	8	9.72	11.63	11.45
2	3	5	9	9.72	11.52	12.65
2	3	5	10	9.72	9.53	13.35
2	3	5	11	9.72	8.31	15.65
2	3	5	12	9.72	5.37	16.77
2	3	5	13	9.72	0.00	18.89

Basic Simulation Results for Figure 5.11- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
1	3	3	1	10.29	17.26	0.00
1	3	3	2	10.29	15.50	4.14
1	3	3	3	10.29	14.90	7.45
1	3	3	4	10.29	14.13	8.45
1	3	3	5	10.29	13.16	9.46
1	3	3	6	10.29	12.98	8.45
1	3	3	7	10.29	12.74	10.37
1	3	3	8	10.29	12.40	10.98
1	3	3	9	10.29	11.98	11.47
1	3	3	10	10.29	10.82	13.09
1	3	3	11	10.29	9.07	13.26
1	3	3	12	10.29	6.13	14.35
1	3	3	13	10.29	0.00	17.13
1	3	4	1	11.84	20.92	0.00
1	3	4	2	11.84	18.97	6.25
1	3	4	3	11.84	17.86	9.25
1	3	4	4	11.84	16.40	10.25
1	3	4	5	11.84	15.80	11.25
1	3	4	6	11.84	14.80	12.45
1	3	4	7	11.84	14.37	13.13
1	3	4	8	11.84	13.65	13.25
1	3	4	9	11.84	13.59	14.25
1	3	4	10	11.84	11.54	15.25
1	3	4	11	11.84	10.22	16.45
1	3	4	12	11.84	6.72	18.45
1	3	4	13		0.00	20.77
2	3	6	1	11.75	23.02	0.00
2	3	6	2	11.75	20.45	5.64
2	3	6	3	11.75	19.36	8.87
2	3	6	4	11.75	17.19	10.25
2	3	6	5	11.75	16.19	11.98
2	3	6	6	11.75	15.17	12.25
2	3	6	7	11.75	14.43	13.25
2	3	6	8	11.75	13.72	14.32
2	3	6	9	11.75	13.81	15.25
2	3	6	10	11.75	11.34	16.25
2	3	6	11	11.75	9.84	18.21
2	3	6	12	11.75	6.46	18.25
2	3	6	13		0.00	22.88

Basic Simulation Results for Figure 5.11- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
1	3	5	1	13.55	24.31	0.00
1	3	5	2	13.55	21.42	6.40
1	3	5	3	13.55	19.90	8.25
1	3	5	4	13.55	18.53	9.25
1	3	5	5	13.55	16.98	11.78
1	3	5	6	13.55	16.01	13.25
1	3	5	7	13.55	15.92	15.17
1	3	5	8	13.55	15.11	15.45
1	3	5	9	13.55	14.68	17.29
1	3	5	10	13.55	12.80	18.25
1	3	5	11	13.55	10.74	19.45
1	3	5	12	13.55	7.35	20.98
1	3	5	13		0.00	24.12
1	3	6	1	15.09	27.85	0.00
1	3	6	2	15.09	24.72	7.45
1	3	6	3	15.09	22.54	11.06
1	3	6	4	15.09	21.03	13.25
1	3	6	5	15.09	19.88	15.45
1	3	6	6	15.09	18.67	16.25
1	3	6	7	15.09	17.76	16.55
1	3	6	8	15.09	17.12	17.26
1	3	6	9	15.09	16.91	18.98
1	3	6	10	15.09	14.00	20.12
1	3	6	11	15.09	12.36	21.45
1	3	6	12	15.09	8.15	23.47
1	3	6	13		0.00	27.35
0	3	3	1	16.58	26.68	0.00
0	3	3	2	16.58	23.93	10.25
0	3	3	3	16.58	23.01	12.25
0	3	3	4	16.58	21.83	15.25
0	3	3	5	16.58	20.44	16.55
0	3	3	6	16.58	20.19	17.98
0	3	3	7	16.58	19.84	18.05
0	3	3	8	16.58	19.27	18.25
0	3	3	9	16.58	18.58	19.25
0	3	3	10	16.58	16.80	21.05
0	3	3	11	16.58	14.14	22.65
0	3	3	12		9.52	23.88
0	3	3	13		0.00	26.58

Basic Simulation Results for Figure 5.11- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
0	3	4	1	16.52	28.52	0.00
0	3	4	2	16.52	25.47	7.26
0	3	4	3	16.52	23.28	11.84
0	3	4	4	16.52	21.99	14.25
0	3	4	5	16.52	20.60	16.58
0	3	4	6	16.52	19.91	17.32
0	3	4	7	16.52	19.68	17.23
0	3	4	8	16.52	18.52	18.55
0	3	4	9	16.52	16.09	19.22
0	3	4	10	16.52	13.84	19.88
0	3	4	11	16.52	11.25	21.45
0	3	4	12	16.52	9.57	24.87
0	3	4	13		0.00	28.32
0	3	5	1	18.33	28.69	0.00
0	3	5	2	18.33	26.24	8.41
0	3	5	3	18.33	24.89	12.25
0	3	5	4	18.33	22.67	15.87
0	3	5	5	18.33	22.11	18.15
0	3	5	6	18.33	20.64	18.45
0	3	5	7	18.33	20.19	19.45
0	3	5	8	18.33	19.23	19.70
0	3	5	9	18.33	19.16	21.58
0	3	5	10	18.33	16.19	23.78
0	3	5	11	18.33	14.42	24.54
0	3	5	12	18.33	9.64	25.98
0	3	5	13		0.00	28.45
0	3	6	1	19.10	31.50	0.00
0	3	6	2	19.10	27.03	9.87
0	3	6	3	19.10	25.27	13.98
0	3	6	4	19.10	23.95	14.17
0	3	6	5	19.10	22.78	16.25
0	3	6	6	19.10	22.29	19.01
0	3	6	7	19.10	21.97	19.27
0	3	6	8	19.10	21.63	21.07
0	3	6	9	19.10	19.16	22.15
0	3	6	10	19.10	16.83	22.45
0	3	6	11	19.10	15.20	24.25
0	3	6	12	19.10	10.40	27.87
0	3	6	13		0.00	31.20

Basic Simulation Results for Figure 5.12

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
3	3	4	1	3.86	8.49	0.00
3	3	4	2	3.86	7.61	2.01
3	3	4	3	3.86	7.03	2.88
3	3	4	4	3.86	6.66	2.98
3	3	4	5	3.86	6.58	3.01
3	3	4	6	3.86	6.30	3.25
3	3	4	7	3.86	5.99	3.45
3	3	4	8	3.86	5.91	3.98
3	3	4	9	3.86	5.89	4.01
3	3	4	10	3.86	5.71	4.17
3	3	4	11	3.86	5.67	4.24
3	3	4	12	3.86	5.48	4.45
3	3	4	13	3.86	5.32	4.98
3	3	4	14	3.86	5.28	5.01
3	3	4	15	3.86	4.92	5.32
3	3	4	16	3.86	4.60	5.45
3	3	4	17	3.86	4.30	6.12
3	3	4	18	3.86	3.87	6.33
3	3	4	19	3.86	3.35	6.55
3	3	4	20	3.86	2.30	7.51
3	3	4	21		0.00	8.40
2	3	3	1	4.80	8.31	0.00
2	3	3	2	4.80	7.71	2.88
2	3	3	3	4.80	7.54	3.98
2	3	3	4	4.80	7.50	4.01
2	3	3	5	4.80	7.12	4.67
2	3	3	6	4.80	7.32	4.88
2	3	3	7	4.80	7.26	5.07
2	3	3	8	4.80	6.98	5.17
2	3	3	9	4.80	6.88	5.36
2	3	3	10	4.80	6.75	5.66
2	3	3	11	4.80	6.66	5.98
2	3	3	12	4.80	6.59	6.07
2	3	3	13	4.80	6.50	6.14
2	3	3	14	4.80	6.35	6.58
2	3	3	15	4.80	6.25	6.99
2	3	3	16	4.80	6.13	7.01
2	3	3	17	4.80	5.22	7.06
2	3	3	18	4.80	4.92	7.27
2	3	3	19	4.80	4.27	7.36
2	3	3	20	4.80	3.08	7.55
2	3	3	21		0.00	8.22

Basic Simulation Results for Figure 5.12- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
3	3	5	2	6.83	12.77	2.98
3	3	5	3	6.83	12.03	4.55
3	3	5	4	6.83	11.71	5.88
3	3	5	5	6.83	10.94	6.98
3	3	5	6	6.83	10.80	7.55
3	3	5	7	6.83	10.96	8.25
3	3	5	8	6.83	10.96	8.55
3	3	5	9	6.83	10.48	9.34
3	3	5	10	6.83	9.84	9.45
3	3	5	11	6.83	9.79	9.65
3	3	5	12	6.83	9.54	9.78
3	3	5	13	6.83	8.98	9.88
3	3	5	14	6.83	8.92	10.02
3	3	5	15	6.83	8.23	10.25
3	3	5	16	6.83	7.75	10.35
3	3	5	17	6.83	7.36	10.55
3	3	5	18	6.83	6.36	10.99
3	3	5	19	6.83	5.49	11.08
3	3	5	20	6.83	3.68	12.44
3	3	5	21		0.00	14.25
2	3	4	1	7.11	14.05	0.00
2	3	4	2	7.11	12.84	3.98
2	3	4	3	7.11	12.10	5.65
2	3	4	4	7.11	11.63	5.21
2	3	4	5	7.11	11.72	6.99
2	3	4	6	7.11	11.30	6.58
2	3	4	7	7.11	10.68	8.98
2	3	4	8	7.11	10.29	8.77
2	3	4	9	7.11	10.38	9.32
2	3	4	10	7.11	9.69	9.35
2	3	4	11	7.11	9.56	9.44
2	3	4	12	7.11	9.40	9.98
2	3	4	13	7.11	9.14	10.07
2	3	4	14	7.11	8.51	10.17
2	3	4	15	7.11	8.24	10.25
2	3	4	16	7.11	7.73	10.98
2	3	4	17	7.11	7.61	11.02
2	3	4	18	7.11	6.97	11.45
2	3	4	19	7.11	6.03	12.22
2	3	4	20	7.11	4.34	12.45
2	3	4	21		0.00	13.96

Basic Simulation Results for Figure 5.12- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
3	3	6	1	9.18	18.78	0.00
3	3	6	2	9.18	16.92	3.44
3	3	6	3	9.18	15.86	6.25
3	3	6	4	9.18	15.62	8.01
3	3	6	5	9.18	15.57	9.35
3	3	6	6	9.18	15.18	9.88
3	3	6	7	9.18	14.09	10.01
3	3	6	8	9.18	13.29	10.25
3	3	6	9	9.18	13.27	10.65
3	3	6	10	9.18	12.67	11.05
3	3	6	11	9.18	12.36	11.45
3	3	6	12	9.18	12.24	11.88
3	3	6	13	9.18	11.75	12.08
3	3	6	14	9.18	10.91	12.55
3	3	6	15	9.18	10.35	12.88
3	3	6	16	9.18	9.71	13.02
3	3	6	17	9.18	9.45	13.15
3	3	6	18	9.18	8.43	13.45
3	3	6	19	9.18	7.18	14.88
3	3	6	20	9.18	4.99	15.65
3	3	6	21		0.00	18.68
2	3	5	1	9.72	19.36	0.00
2	3	5	2	9.72	18.76	4.12
2	3	5	3	9.72	16.48	7.05
2	3	5	4	9.72	15.40	8.01
2	3	5	5	9.72	15.43	8.12
2	3	5	6	9.72	14.23	8.25
2	3	5	7	9.72	13.63	8.99
2	3	5	8	9.72	13.44	9.01
2	3	5	9	9.72	12.89	9.14
2	3	5	10	9.72	12.83	9.25
2	3	5	11	9.72	12.52	11.05
2	3	5	12	9.72	12.34	11.35
2	3	5	13	9.72	12.12	11.55
2	3	5	14	9.72	11.61	11.98
2	3	5	15	9.72	11.18	12.05
2	3	5	16	9.72	10.59	12.55
2	3	5	17	9.72	9.51	13.96
2	3	5	18	9.72	9.20	14.99
2	3	5	19	9.72	7.28	16.22
2	3	5	20	9.72	5.26	18.55
2	3	5	21		0.00	19.22

Basic Simulation Results for Figure 5.12- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
1	3	3	1	10.29	17.09	0.00
1	3	3	2	10.29	16.20	4.25
1	3	3	3	10.29	15.22	5.65
1	3	3	4	10.29	15.11	8.25
1	3	3	5	10.29	14.94	8.54
1	3	3	6	10.29	14.40	9.78
1	3	3	7	10.29	14.36	10.98
1	3	3	8	10.29	14.25	11.01
1	3	3	9	10.29	14.11	11.78
1	3	3	10	10.29	13.58	12.25
1	3	3	11	10.29	13.52	12.35
1	3	3	12	10.29	13.51	12.88
1	3	3	13	10.29	13.00	13.07
1	3	3	14	10.29	12.44	13.12
1	3	3	15	10.29	11.41	13.20
1	3	3	16	10.29	11.38	13.24
1	3	3	17	10.29	10.37	13.88
1	3	3	18	10.29	9.01	14.65
1	3	3	19	10.29	6.61	14.88
1	3	3	20	10.29	5.56	15.78
1	3	3	21		0.00	16.88
1	3	4	1	11.84	21.10	0.00
1	3	4	2	11.84	19.05	5.35
1	3	4	3	11.84	18.63	8.25
1	3	4	4	11.84	17.40	10.99
1	3	4	5	11.84	16.95	11.25
1	3	4	6	11.84	16.24	11.42
1	3	4	7	11.84	15.65	12.69
1	3	4	8	11.84	15.62	12.88
1	3	4	9	11.84	14.90	13.04
1	3	4	10	11.84	14.68	13.25
1	3	4	11	11.84	14.54	13.44
1	3	4	12	11.84	14.51	13.88
1	3	4	13	11.84	14.09	14.15
1	3	4	14	11.84	13.78	14.25
1	3	4	15	11.84	13.31	15.25
1	3	4	16	11.84	12.68	15.87
1	3	4	17	11.84	11.51	16.25
1	3	4	18	11.84	11.31	16.65
1	3	4	19	11.84	9.19	18.25
1	3	4	20	11.84	6.70	18.99
1	3	4	21		0.00	21.05

Basic Simulation Results for Figure 5.12- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
2	3	6	1	11.75	23.09	0.00
2	3	6	2	11.75	20.29	5.88
2	3	6	3	11.75	19.56	7.24
2	3	6	4	11.75	18.21	10.45
2	3	6	5	11.75	18.15	11.88
2	3	6	6	11.75	17.25	11.65
2	3	6	7	11.75	16.10	12.05
2	3	6	8	11.75	15.52	12.55
2	3	6	9	11.75	15.13	13.11
2	3	6	10	11.75	15.09	13.65
2	3	6	11	11.75	14.60	13.90
2	3	6	12	11.75	14.28	14.05
2	3	6	13	11.75	14.11	14.35
2	3	6	14	11.75	13.68	15.25
2	3	6	15	11.75	13.25	15.01
2	3	6	16	11.75	12.45	17.65
2	3	6	17	11.75	11.02	17.88
2	3	6	18	11.75	10.72	18.01
2	3	6	19	11.75	8.43	19.25
2	3	6	20	11.75	6.10	21.88
2	3	6	21		0.00	22.99
1	3	5	1	13.55	24.49	0.00
1	3	5	2	13.55	22.46	6.15
1	3	5	3	13.55	21.10	9.25
1	3	5	4	13.55	20.54	10.15
1	3	5	5	13.55	20.48	10.25
1	3	5	6	13.55	19.94	11.88
1	3	5	7	13.55	18.66	13.17
1	3	5	8	13.55	17.85	13.25
1	3	5	9	13.55	17.76	14.05
1	3	5	10	13.55	16.81	14.65
1	3	5	11	13.55	16.66	15.66
1	3	5	12	13.55	16.43	16.09
1	3	5	13	13.55	15.82	16.14
1	3	5	14	13.55	14.81	16.37
1	3	5	15	13.55	14.10	18.35
1	3	5	16	13.55	13.35	18.65
1	3	5	17	13.55	13.01	19.25
1	3	5	18	13.55	11.90	19.54
1	3	5	19	13.55	10.56	19.99
1	3	5	20	13.55	7.49	22.24
1	3	5	21		0.00	24.39

Basic Simulation Results for Figure 5.12- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
1	3	6	1	15.09	27.91	0.00
1	3	6	2	15.09	24.55	6.25
1	3	6	3	15.09	23.85	9.25
1	3	6	4	15.09	22.15	12.66
1	3	6	5	15.09	21.98	15.47
1	3	6	6	15.09	21.00	16.25
1	3	6	7	15.09	19.67	16.66
1	3	6	8	15.09	19.22	17.09
1	3	6	9	15.09	18.65	17.25
1	3	6	10	15.09	18.59	17.65
1	3	6	11	15.09	18.15	18.13
1	3	6	12	15.09	17.75	18.74
1	3	6	13	15.09	17.67	18.88
1	3	6	14	15.09	16.96	19.15
1	3	6	15	15.09	16.38	19.25
1	3	6	16	15.09	15.50	19.88
1	3	6	17	15.09	13.84	21.45
1	3	6	18	15.09	13.33	22.45
1	3	6	19	15.09	10.56	22.99
1	3	6	20	15.09	7.86	23.25
1	3	6	21		0.00	26.11
0	3	3	1	16.58	26.35	0.00
0	3	3	2	16.58	25.02	8.14
0	3	3	3	16.58	23.49	9.14
0	3	3	4	16.58	23.19	12.14
0	3	3	5	16.58	22.98	13.25
0	3	3	6	16.58	22.32	16.25
0	3	3	7	16.58	22.16	17.25
0	3	3	8	16.58	22.05	17.45
0	3	3	9	16.58	21.84	17.98
0	3	3	10	16.58	20.91	18.24
0	3	3	11	16.58	20.90	19.15
0	3	3	12	16.58	20.19	19.45
0	3	3	13	16.58	19.32	19.98
0	3	3	14	16.58	18.71	20.14
0	3	3	15	16.58	17.59	21.47
0	3	3	16	16.58	17.57	21.65
0	3	3	17	16.58	15.94	21.74
0	3	3	18	16.58	13.93	22.01
0	3	3	19	16.58	10.20	22.14
0	3	3	20	16.58	9.28	24.87
0	3	3	21		0.00	27.66

Basic Simulation Results for Figure 5.12- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
0	3	4	1	16.52	28.79	0.00
0	3	4	2	16.52	26.09	11.08
0	3	4	3	16.52	25.73	14.10
0	3	4	4	16.52	24.03	14.25
0	3	4	5	16.52	23.47	15.24
0	3	4	6	16.52	22.45	17.14
0	3	4	7	16.52	21.89	17.65
0	3	4	8	16.52	21.78	18.35
0	3	4	9	16.52	20.77	18.54
0	3	4	10	16.52	20.40	18.65
0	3	4	11	16.52	20.38	19.47
0	3	4	12	16.52	20.35	19.65
0	3	4	13	16.52	19.72	19.55
0	3	4	14	16.52	19.15	20.14
0	3	4	15	16.52	18.57	20.98
0	3	4	16	16.52	17.93	21.12
0	3	4	17	16.52	16.41	21.41
0	3	4	18	16.52	16.07	22.03
0	3	4	19	16.52	13.17	25.42
0	3	4	20	16.52	9.62	25.98
0	3	4	21		0.00	28.45
0	3	5	1	18.33	30.58	0.00
0	3	5	2	18.33	27.72	8.55
0	3	5	3	18.33	26.46	9.98
0	3	5	4	18.33	25.45	12.24
0	3	5	5	18.33	24.26	12.25
0	3	5	6	18.33	24.05	14.25
0	3	5	7	18.33	24.38	16.25
0	3	5	8	18.33	24.85	18.24
0	3	5	9	18.33	23.41	19.85
0	3	5	10	18.33	22.75	19.65
0	3	5	11	18.33	22.25	20.98
0	3	5	12	18.33	21.76	21.05
0	3	5	13	18.33	21.07	22.41
0	3	5	14	18.33	20.88	23.05
0	3	5	15	18.33	19.18	23.14
0	3	5	16	18.33	18.21	23.45
0	3	5	17	18.33	17.20	23.87
0	3	5	18	18.33	15.37	24.15
0	3	5	19	18.33	13.61	25.98
0	3	5	20	18.33	9.52	27.45
0	3	5	21		0.00	30.25

Basic Simulation Results for Figure 5.12- cont'd

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
0	3	6	1	19.10	32.60	0.00
0	3	6	2	19.10	29.40	9.07
0	3	6	3	19.10	27.55	12.09
0	3	6	4	19.10	26.18	15.24
0	3	6	5	19.10	25.86	16.58
0	3	6	6	19.10	24.87	18.74
0	3	6	7	19.10	23.87	19.87
0	3	6	8	19.10	23.33	20.87
0	3	6	9	19.10	22.85	20.98
0	3	6	10	19.10	22.65	21.12
0	3	6	11	19.10	22.48	21.32
0	3	6	12	19.10	22.08	21.45
0	3	6	13	19.10	21.59	21.65
0	3	6	14	19.10	21.29	21.75
0	3	6	15	19.10	20.05	22.35
0	3	6	16	19.10	18.98	22.65
0	3	6	17	19.10	17.93	24.38
0	3	6	18	19.10	16.26	25.99
0	3	6	19	19.10	13.89	26.45
0	3	6	20	19.10	10.28	28.98
0	3	6	21		0.00	32.45

Basic Simulation Results for Figure 5.13

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
3	3	4	1	7.67	6.96
3	3	4	2	6.40	5.29
3	3	4	3	5.12	4.07
3	3	4	4	3.84	2.61
2	3	3	1	9.02	7.44
2	3	3	2	7.48	6.14
2	3	3	3	5.95	4.93
2	3	3	4	4.41	3.46
3	3	5	1	11.91	11.93
3	3	5	2	9.82	9.07
3	3	5	3	7.73	7.01
3	3	5	4	5.64	4.47
2	3	4	1	12.31	11.95
2	3	4	2	10.15	9.34
2	3	4	3	7.98	7.34
2	3	4	4	5.81	4.93
3	3	6	1	15.27	15.70
3	3	6	2	12.54	11.97
3	3	6	3	9.80	9.25
3	3	6	4	7.07	5.91
2	3	5	1	16.04	16.15
2	3	5	2	13.16	12.43
2	3	5	3	10.28	9.69
2	3	5	4	7.40	6.33
1	3	3	1	16.85	15.56
1	3	3	2	13.82	12.83
1	3	3	3	10.78	10.41
1	3	3	4	7.74	7.20
1	3	4	1	19.07	18.27
1	3	4	2	15.61	14.61
1	3	4	3	12.14	11.66
1	3	4	4	8.68	7.99

Basic Simulation Results for Figure 5.13 – cont'd

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
2	3	6	1	18.94	19.43
2	3	6	2	15.50	14.84
2	3	6	3	12.07	11.59
2	3	6	4	8.63	7.46
1	3	5	1	21.51	21.37
1	3	5	2	17.58	16.72
1	3	5	3	13.65	13.15
1	3	5	4	9.72	8.79
1	3	6	1	23.70	23.87
1	3	6	2	19.36	18.43
1	3	6	3	15.01	14.50
1	3	6	4	10.66	9.53
0	3	3	1	25.83	24.33
0	3	3	2	21.07	20.16
0	3	3	3	16.32	16.30
0	3	3	4	11.56	11.27
0	3	4	1	25.75	24.49
0	3	4	2	21.01	20.63
0	3	4	3	16.26	16.62
0	3	4	4	11.52	11.40
0	3	5	1	28.33	27.36
0	3	5	2	23.09	21.62
0	3	5	3	17.86	17.15
0	3	5	4	12.62	11.64
0	3	6	1	29.43	28.91
0	3	6	2	23.98	22.58
0	3	6	3	18.54	17.87
0	3	6	4	13.09	11.94

Basic Simulation Results for Figure 5.14

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
3	3	4	1	7.98	7.54
3	3	4	2	7.27	5.23
3	3	4	3	6.57	5.53
3	3	4	4	5.87	4.93
3	3	4	5	5.17	4.13
3	3	4	6	4.46	3.43
3	3	4	7	3.76	2.22
2	3	3	1	9.34	7.74
2	3	3	2	8.51	7.05
2	3	3	3	7.68	6.34
2	3	3	4	6.85	5.82
2	3	3	5	6.02	5.12
2	3	3	6	5.19	4.72
2	3	3	7	4.35	3.16
3	3	5	1	12.29	12.76
3	3	5	2	11.18	10.90
3	3	5	3	10.07	9.65
3	3	5	4	8.96	8.68
3	3	5	5	7.85	7.52
3	3	5	6	6.74	6.49
3	3	5	7	5.63	3.93
2	3	4	1	12.69	13.22
2	3	4	2	11.55	11.48
2	3	4	3	10.40	10.36
2	3	4	4	9.25	9.32
2	3	4	5	8.10	8.39
2	3	4	6	6.96	7.06
2	3	4	7	5.81	5.39
3	3	6	1	15.70	17.34
3	3	6	2	14.27	14.88
3	3	6	3	12.84	13.31
3	3	6	4	11.41	11.96
3	3	6	5	9.98	10.56
3	3	6	6	8.55	9.14
3	3	6	7	7.12	6.48
2	3	5	1	16.48	17.28
2	3	5	2	14.98	14.64
2	3	5	3	13.47	12.92
2	3	5	4	11.97	11.82
2	3	5	5	10.46	10.70
2	3	5	6	8.96	9.08
2	3	5	7	7.46	5.72

Basic Simulation Results for Figure 5.14 – cont'd

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
1	3	3	1	17.31	16.73
1	3	3	2	15.73	15.18
1	3	3	3	14.14	14.19
1	3	3	4	12.56	12.75
1	3	3	5	10.98	11.40
1	3	3	6	9.40	9.91
1	3	3	7	7.82	7.92
1	3	4	1	19.56	19.95
1	3	4	2	17.76	17.01
1	3	4	3	15.97	15.24
1	3	4	4	14.17	13.98
1	3	4	5	12.38	12.81
1	3	4	6	10.59	10.92
1	3	4	7	8.79	7.32
2	3	6	1	19.43	21.11
2	3	6	2	17.64	17.35
2	3	6	3	15.86	15.35
2	3	6	4	14.08	14.04
2	3	6	5	12.30	12.81
2	3	6	6	10.52	11.10
2	3	6	7	8.74	6.81
1	3	5	1	22.04	23.37
1	3	5	2	20.01	20.16
1	3	5	3	17.98	17.96
1	3	5	4	15.95	16.58
1	3	5	5	13.93	14.80
1	3	5	6	11.90	12.53
1	3	5	7	9.87	9.41
1	3	6	1	24.27	25.99
1	3	6	2	22.03	21.50
1	3	6	3	19.79	18.96
1	3	6	4	17.56	17.33
1	3	6	5	15.32	15.91
1	3	6	6	13.08	13.81
1	3	6	7	10.84	8.64
0	3	3	1	26.43	25.92
0	3	3	2	23.99	23.62
0	3	3	3	21.55	22.15
0	3	3	4	19.11	19.85
0	3	3	5	16.66	17.77
0	3	3	6	14.22	15.44
0	3	3	7	11.78	12.33
0	3	4	1	26.35	27.34
0	3	4	2	23.91	23.52
0	3	4	3	21.48	21.16
0	3	4	4	19.04	19.51
0	3	4	5	16.61	18.12
0	3	4	6	14.18	15.43
0	3	4	7	11.74	10.47

Basic Simulation Results for Figure 5.14 – cont'd

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
0	3	5	1	28.97	28.32
0	3	5	2	26.29	24.99
0	3	5	3	23.61	22.14
0	3	5	4	20.93	20.01
0	3	5	5	18.25	17.55
0	3	5	6	15.56	15.99
0	3	5	7	12.88	10.14
0	3	6	1	30.09	30.96
0	3	6	2	27.30	25.81
0	3	6	3	24.52	23.26
0	3	6	4	21.73	21.13
0	3	6	5	18.94	17.81
0	3	6	6	16.16	14.89
0	3	6	7	13.37	10.07

Basic Simulation Results for Figure 5.15

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
3	3	4	1	8.48	8.19
3	3	4	2	8.04	7.21
3	3	4	3	7.60	6.43
3	3	4	4	7.16	5.86
3	3	4	5	6.72	5.54
3	3	4	6	6.28	5.08
3	3	4	7	5.83	4.84
3	3	4	8	5.39	4.75
3	3	4	9	4.95	4.43
3	3	4	10	4.51	3.80
3	3	4	11	4.07	3.22
3	3	4	12	3.63	2.14
2	3	3	1	9.88	8.16
2	3	3	2	9.37	7.50
2	3	3	3	8.86	7.22
2	3	3	4	8.35	7.07
2	3	3	5	7.84	6.87
2	3	3	6	7.33	6.57
2	3	3	7	6.81	6.51
2	3	3	8	6.30	6.45
2	3	3	9	5.79	5.67
2	3	3	10	5.28	5.10
2	3	3	11	4.77	4.66
2	3	3	12	4.26	6.07
3	3	5	1	12.91	14.06
3	3	5	2	12.24	12.31
3	3	5	3	11.58	11.29
3	3	5	4	10.92	10.81
3	3	5	5	10.26	10.10
3	3	5	6	9.59	9.88
3	3	5	7	8.93	9.44
3	3	5	8	8.27	9.29
3	3	5	9	7.61	8.33
3	3	5	10	6.94	7.11
3	3	5	11	6.28	6.18
3	3	5	12	5.62	4.06
2	3	4	1	13.32	13.79
2	3	4	2	12.64	12.25
2	3	4	3	11.96	11.50
2	3	4	4	11.27	10.67
2	3	4	5	10.59	9.67
2	3	4	6	9.91	9.26
2	3	4	7	9.22	8.92
2	3	4	8	8.54	8.48
2	3	4	9	7.86	8.27
2	3	4	10	7.17	7.31
2	3	4	11	6.49	6.07
2	3	4	12	5.80	4.21
3	3	6	1	16.41	18.50
3	3	6	2	15.57	16.19
3	3	6	3	14.73	14.90
3	3	6	4	13.90	13.88
3	3	6	5	13.06	12.69
3	3	6	6	12.22	11.86
3	3	6	7	11.38	11.57
3	3	6	8	10.54	11.13
3	3	6	9	9.71	10.61
3	3	6	10	8.87	9.08
3	3	6	11	8.03	7.50
3	3	6	12	7.19	5.07

Basic Simulation Results for Figure 5.15 – cont'd

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
2	3	5	1	17.21	19.13
2	3	5	2	16.34	17.00
2	3	5	3	15.46	16.08
2	3	5	4	14.58	14.52
2	3	5	5	13.70	13.68
2	3	5	6	12.82	12.86
2	3	5	7	11.94	12.26
2	3	5	8	11.07	11.63
2	3	5	9	10.19	11.52
2	3	5	10	9.31	9.53
2	3	5	11	8.43	8.31
2	3	5	12	7.55	5.37
1	3	3	1	18.06	17.26
1	3	3	2	17.14	15.50
1	3	3	3	16.22	14.90
1	3	3	4	15.30	14.13
1	3	3	5	14.38	13.16
1	3	3	6	13.46	12.98
1	3	3	7	12.54	12.74
1	3	3	8	11.62	12.40
1	3	3	9	10.70	11.98
1	3	3	10	9.78	10.82
1	3	3	11	8.85	9.07
1	3	3	12	7.93	6.13
1	3	4	1	20.37	20.92
1	3	4	2	19.34	18.97
1	3	4	3	18.30	17.86
1	3	4	4	17.26	16.40
1	3	4	5	16.23	15.80
1	3	4	6	15.19	14.80
1	3	4	7	14.15	14.37
1	3	4	8	13.12	13.65
1	3	4	9	12.08	13.59
1	3	4	10	11.04	11.54
1	3	4	11	10.01	10.22
1	3	4	12	8.97	6.72
2	3	6	1	20.24	23.02
2	3	6	2	19.21	20.45
2	3	6	3	18.18	19.36
2	3	6	4	17.15	17.19
2	3	6	5	16.12	16.19
2	3	6	6	15.09	15.17
2	3	6	7	14.06	14.43
2	3	6	8	13.03	13.72
2	3	6	9	12.00	13.81
2	3	6	10	10.97	11.34
2	3	6	11	9.94	9.84
2	3	6	12	8.91	6.46
1	3	5	1	22.92	24.31
1	3	5	2	21.76	21.42
1	3	5	3	20.59	19.90
1	3	5	4	19.43	18.53
1	3	5	5	18.27	16.98
1	3	5	6	17.10	16.01
1	3	5	7	15.94	15.92
1	3	5	8	14.77	15.11
1	3	5	9	13.61	14.68
1	3	5	10	12.45	12.80
1	3	5	11	11.28	10.74
1	3	5	12	10.12	7.35

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Basic Simulation Results for Figure 5.16

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
3	3	4	1	9.29	8.49
3	3	4	2	8.98	7.61
3	3	4	3	8.67	7.03
3	3	4	4	8.36	6.66
3	3	4	5	8.05	6.58
3	3	4	6	7.74	6.30
3	3	4	7	7.43	5.99
3	3	4	8	7.12	5.91
3	3	4	9	6.82	5.89
3	3	4	10	6.51	5.71
3	3	4	11	6.20	5.67
3	3	4	12	5.89	5.48
3	3	4	13	5.58	5.32
3	3	4	14	5.27	5.28
3	3	4	15	4.96	4.92
3	3	4	16	4.65	4.60
3	3	4	17	4.34	4.30
3	3	4	18	4.03	3.87
3	3	4	19	3.72	3.35
3	3	4	20	3.42	2.30
2	3	3	1	10.75	8.31
2	3	3	2	10.40	7.71
2	3	3	3	10.05	7.54
2	3	3	4	9.70	7.50
2	3	3	5	9.35	7.32
2	3	3	6	9.00	7.26
2	3	3	7	8.65	7.12
2	3	3	8	8.30	6.98
2	3	3	9	7.95	6.88
2	3	3	10	7.60	6.75
2	3	3	11	7.25	6.66
2	3	3	12	6.90	6.59
2	3	3	13	6.55	6.50
2	3	3	14	6.20	6.35
2	3	3	15	5.85	6.25
2	3	3	16	5.50	6.13
2	3	3	17	5.15	5.22
2	3	3	18	4.80	4.92
2	3	3	19	4.45	4.27
2	3	3	20	4.10	3.08

Basic Simulation Results for Figure 5.16 – cont'd

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
3	3	5	1	13.90	14.46
3	3	5	2	13.46	12.77
3	3	5	3	13.03	12.03
3	3	5	4	12.59	11.71
3	3	5	5	12.15	10.94
3	3	5	6	11.71	10.80
3	3	5	7	11.28	10.96
3	3	5	8	10.84	10.96
3	3	5	9	10.40	10.48
3	3	5	10	9.96	9.84
3	3	5	11	9.53	9.79
3	3	5	12	9.09	9.54
3	3	5	13	8.65	8.98
3	3	5	14	8.21	8.92
3	3	5	15	7.78	8.23
3	3	5	16	7.34	7.75
3	3	5	17	6.90	7.36
3	3	5	18	6.47	6.36
3	3	5	19	6.03	5.49
3	3	5	20	5.59	3.68
2	3	4	1	14.34	14.05
2	3	4	2	13.89	12.84
2	3	4	3	13.44	12.10
2	3	4	4	12.99	11.63
2	3	4	5	12.54	11.30
2	3	4	6	12.09	11.72
2	3	4	7	11.64	10.68
2	3	4	8	11.19	10.29
2	3	4	9	10.74	10.38
2	3	4	10	10.29	9.69
2	3	4	11	9.84	9.40
2	3	4	12	9.39	9.56
2	3	4	13	8.94	9.14
2	3	4	14	8.49	8.51
2	3	4	15	8.04	8.24
2	3	4	16	7.59	7.73
2	3	4	17	7.14	7.61
2	3	4	18	6.69	6.97
2	3	4	19	6.25	6.03
2	3	4	20	5.80	4.34

Basic Simulation Results for Figure 5.16 – cont'd

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
3	3	6	1	17.55	18.78
3	3	6	2	17.01	16.92
3	3	6	3	16.47	15.86
3	3	6	4	15.93	15.62
3	3	6	5	15.39	15.57
3	3	6	6	14.86	15.18
3	3	6	7	14.32	14.09
3	3	6	8	13.78	13.29
3	3	6	9	13.24	13.27
3	3	6	10	12.70	12.67
3	3	6	11	12.16	12.36
3	3	6	12	11.62	12.24
3	3	6	13	11.08	11.75
3	3	6	14	10.54	10.91
3	3	6	15	10.01	10.35
3	3	6	16	9.47	9.71
3	3	6	17	8.93	9.45
3	3	6	18	8.39	8.43
3	3	6	19	7.85	7.18
3	3	6	20	7.31	4.99
2	3	5	1	18.39	19.36
2	3	5	2	17.83	17.02
2	3	5	3	17.26	16.48
2	3	5	4	16.70	15.40
2	3	5	5	16.14	15.43
2	3	5	6	15.58	14.23
2	3	5	7	15.02	13.63
2	3	5	8	14.45	13.44
2	3	5	9	13.89	12.89
2	3	5	10	13.33	12.83
2	3	5	11	12.77	12.52
2	3	5	12	12.20	12.34
2	3	5	13	11.64	12.12
2	3	5	14	11.08	11.61
2	3	5	15	10.52	11.18
2	3	5	16	9.96	10.59
2	3	5	17	9.39	9.51
2	3	5	18	8.83	9.20
2	3	5	19	8.27	7.28
2	3	5	20	7.71	5.26

Basic Simulation Results for Figure 5.16 – cont'd

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
1	3	3	1	19.27	17.09
1	3	3	2	18.69	16.20
1	3	3	3	18.10	15.22
1	3	3	4	17.51	15.11
1	3	3	5	16.93	14.94
1	3	3	6	16.34	14.40
1	3	3	7	15.75	14.36
1	3	3	8	15.17	14.25
1	3	3	9	14.58	14.11
1	3	3	10	13.99	13.58
1	3	3	11	13.41	13.52
1	3	3	12	12.82	13.51
1	3	3	13	12.23	13.00
1	3	3	14	11.65	12.44
1	3	3	15	11.06	11.41
1	3	3	16	10.47	11.38
1	3	3	17	9.88	10.37
1	3	3	18	9.30	9.01
1	3	3	19	8.71	6.61
1	3	3	20	8.12	5.56
1	3	4	1	21.68	21.10
1	3	4	2	21.03	19.05
1	3	4	3	20.37	18.63
1	3	4	4	19.72	17.40
1	3	4	5	19.07	16.95
1	3	4	6	18.41	16.24
1	3	4	7	17.76	15.65
1	3	4	8	17.10	15.62
1	3	4	9	16.45	14.90
1	3	4	10	15.80	14.68
1	3	4	11	15.14	14.54
1	3	4	12	14.49	14.51
1	3	4	13	13.84	14.09
1	3	4	14	13.18	13.78
1	3	4	15	12.53	13.31
1	3	4	16	11.87	12.68
1	3	4	17	11.22	11.51
1	3	4	18	10.57	11.31
1	3	4	19	9.91	9.19
1	3	4	20	9.26	6.70

Basic Simulation Results for Figure 5.16 – cont'd

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
2	3	6	1	21.54	23.09
2	3	6	2	20.89	20.29
2	3	6	3	20 24	19.56
2	3	6	4	19.59	18.21
2	3	6	5	18.94	18.15
2	3	6	6	18 29	17.25
2	3	6	7	17.64	16.10
2	3	6	8	16 99	15.52
2	3	6	9	16.34	15.13
2	3	6	10	15.69	15.09
2	3	6	11	15.04	14.60
2	3	6	12	14.39	14.28
2	3	6	13	13.74	14.11
2	3	6	14	13.09	13.68
2	3	6	15	12.44	13 25
2	3	6	16	11.79	12.45
2	3	6	17	11.14	11.02
2	3	6	18	10.49	10.72
2	3	6	19	9.84	8.43
2	3	6	20	9.19	6 10
1	3	5	1	24.34	24.49
1	3	5	2	23.61	22 46
1	3	5	3	22 88	21.10
1	3	5	4	22.15	20.54
1	3	5	5	21.43	20.48
1	3	5	6	20.70	19.94
1	3	5	7	19.97	18.66
1	3	5	8	19.24	17.85
1	3	5	9	18.52	17.76
1	3	5	10	17.79	16.81
1	3	5	11	17.06	16.66
1	3	5	12	16.33	16 43
1	3	5	13	15 61	15.82
1	3	5	14	14.88	14 81
1	3	5	15	14.15	14.10
1	3	5	16	13.42	13.35
1	3	5	17	12 69	13.01
1	3	5	18	11.97	11.90
1	3	5	19	11.24	10.56
1	3	5	20	10.51	7.49

Basic Simulation Results for Figure 5.16 – cont'd

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
1	3	6	1	26.73	27.91
1	3	6	2	25.93	24 55
1	3	6	3	25.14	23 85
1	3	6	4	24.35	22.15
1	3	6	5	23.55	21.98
1	3	6	6	22 76	21.00
1	3	6	7	21.96	19 67
1	3	6	8	21.17	19.22
1	3	6	9	20.38	18.65
1	3	6	10	19 58	18.59
1	3	6	11	18.79	18.15
1	3	6	12	17.99	17.75
1	3	6	13	17.20	17.67
1	3	6	14	16.40	16.96
1	3	6	15	15.61	16.38
1	3	6	16	14.82	15.50
1	3	6	17	14 02	13.84
1	3	6	18	13.23	13.33
1	3	6	19	12 43	10.56
1	3	6	20	11.64	7.86
0	3	3	1	29.04	26.35
0	3	3	2	28.18	25.02
0	3	3	3	27.32	23.49
0	3	3	4	26.47	23.19
0	3	3	5	25 61	22 98
0	3	3	6	24.75	22.32
0	3	3	7	23 89	22.16
0	3	3	8	23.03	22 05
0	3	3	9	22.17	21 84
0	3	3	10	21.32	20.91
0	3	3	11	20.46	20 90
0	3	3	12	19.60	20.19
0	3	3	13	18.74	19.32
0	3	3	14	17.88	18.71
0	3	3	15	17.02	17.59
0	3	3	16	16.16	17.57
0	3	3	17	15.31	15.94
0	3	3	18	14.45	13.93
0	3	3	19	13.59	10 20
0	3	3	20	12 73	9 28

Basic Simulation Results for Figure 5.16 – cont'd

a	t	b	WS Position	Estimated %Blocking - from Equation 26	%Blocking - Simulation Results
0	3	4	1	28.95	28.79
0	3	4	2	28.09	26.09
0	3	4	3	27.24	25.73
0	3	4	4	26.38	24.03
0	3	4	5	25.53	23.47
0	3	4	6	24.67	22.45
0	3	4	7	23.81	21.89
0	3	4	8	22.96	21.78
0	3	4	9	22.10	20.77
0	3	4	10	21.25	20.40
0	3	4	11	20.39	20.38
0	3	4	12	19.53	20.35
0	3	4	13	18.68	19.72
0	3	4	14	17.82	19.15
0	3	4	15	16.97	18.57
0	3	4	16	16.11	17.93
0	3	4	17	15.25	16.41
0	3	4	18	14.40	16.07
0	3	4	19	13.54	13.17
0	3	4	20	12.69	9.62
0	3	5	1	31.76	30.58
0	3	5	2	30.83	27.72
0	3	5	3	29.89	26.46
0	3	5	4	28.96	25.45
0	3	5	5	28.02	24.26
0	3	5	6	27.09	24.05
0	3	5	7	26.16	24.38
0	3	5	8	25.22	24.85
0	3	5	9	24.29	23.41
0	3	5	10	23.35	22.75
0	3	5	11	22.42	22.25
0	3	5	12	21.48	21.76
0	3	5	13	20.55	20.79
0	3	5	14	19.62	21.07
0	3	5	15	18.68	19.18
0	3	5	16	17.75	18.21
0	3	5	17	16.81	17.20
0	3	5	18	15.88	15.37
0	3	5	19	14.95	13.61
0	3	5	20	14.01	9.52
0	3	6	1	32.96	32.60
0	3	6	2	31.99	29.40
0	3	6	3	31.02	27.55
0	3	6	4	30.05	26.18
0	3	6	5	29.09	25.86
0	3	6	6	28.12	24.87
0	3	6	7	27.15	23.87
0	3	6	8	26.18	23.33
0	3	6	9	25.22	22.85
0	3	6	10	24.25	22.65
0	3	6	11	23.28	22.46
0	3	6	12	22.31	22.08
0	3	6	13	21.35	21.59
0	3	6	14	20.38	21.29
0	3	6	15	19.41	20.05
0	3	6	16	18.45	18.98
0	3	6	17	17.48	17.93
0	3	6	18	16.51	16.26
0	3	6	19	15.54	13.89
0	3	6	20	14.58	10.28

Basic Simulation Results for Figure 5.20

a	t	b	WS Position	% $B_{1,2}$	Individual Work Station %Blocking	Individual Work Station %Waiting
0	3	3	1	24.33	27.08	0.00
0	3	6	2	22.58	22.24	0.22
0	3	6	3	17.87	19.75	7.5
0	3	6	4	11.94	12.50	14.37
0	3	6	5	0.00	0.00	27.41
0	3	6	1	28.91	25.67	0.00
0	3	3	2	20.16	41.76	8.63
0	3	6	3	17.87	23.21	2.45
0	3	6	4	11.94	13.86	11.11
0	3	6	5	0.00	0.00	24.87
0	3	6	1	28.91	24.71	0.00
0	3	6	2	22.58	14.74	9.76
0	3	3	3	16.30	28.96	20.62
0	3	6	4	11.94	14.60	9.4
0	3	6	5	0.00	0.00	24.56
0	3	6	1	28.91	25.62	0.00
0	3	6	2	22.58	16.44	8.93
0	3	6	3	17.87	6.99	18.34
0	3	3	4	11.27	15.00	34.94
0	3	6	5	0.00	0.00	25.49
0	3	6	1	28.91	27.43	0.00
0	3	6	2	22.58	19.91	7.32
0	3	6	3	17.87	13.20	13.95
0	3	6	4	11.94	2.54	24.25
0	3	3	5	0.00	0.00	27.94

Basic Simulation Results for Figure 5.21

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
0	3	3	1	24.33	49.98	0.00
0	3	3	2	20.16	49.57	0.28
0	3	6	3	17.87	24.28	0.45
0	3	6	4	11.94	14.02	10.28
0	3	6	5	0.00	0.00	50.24
0	3	6	1	28.91	21.08	0.00
0	3	3	2	20.16	33.92	13.31
0	3	3	3	17.87	41.07	6.04
0	3	6	4	11.94	17.28	3.05
0	3	6	5	0.00	0.00	20.9
0	3	6	1	28.91	19.20	0.00
0	3	3	2	20.16	30.69	15.28
0	3	6	3	17.87	11.92	6.92
0	3	3	4	11.27	20.32	25.35
0	3	6	5	0.00	0.00	19.04
0	3	6	1	28.91	20.93	0.00
0	3	6	2	22.58	6.68	14.01
0	3	3	3	16.30	11.74	35.26
0	3	3	4	11.27	19.49	27.29
0	3	6	5	0.00	0.00	20.74
0	3	6	1	28.91	24.84	0.00
0	3	6	2	22.58	14.86	9.76
0	3	6	3	17.87	3.15	21.41
0	3	3	4	11.27	2.76	46.67
0	3	3	5	0.00	0.00	49.79

Basic Simulation Results for Figure 5.22

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
0	3	3	1	24.33	46.68	0.00
0	3	3	2	20.16	46.11	0.46
0	3	3	3	16.30	45.68	0.77
0	3	6	4	11.94	18.05	1.32
0	3	6	5	0.00	0.00	19.91
0	3	6	1	28.91	12.77	0.00
0	3	3	2	20.16	18.27	23.42
0	3	3	3	16.30	24.08	17.5
0	3	3	4	11.27	28.19	13.15
0	3	6	5	0.00	0.00	12.54
0	3	6	1	28.91	19.78	0.00
0	3	6	2	22.58	4.02	15.55
0	3	3	3	16.30	3.96	42.3
0	3	3	4	11.27	3.56	42.5
0	3	3	5	0.00	0.00	46.41

Basic Simulation Results for Figure 5.23

a	t	b	WS Position	% $B_{1,2}$	Individual Workstation %Blocking	Individual Workstation %Waiting
0	3	3	1	24.33	38.53	0.00
0	3	3	2	20.16	37.16	1.27
0	3	3	3	16.30	36.10	2.22
0	3	3	4	11.27	34.41	3.68
0	3	6	5	0.00	0.00	7.77
0	3	6	1	28.91	7.67	0.00
0	3	3	2	20.16	7.09	31.24
0	3	3	3	16.30	7.09	31.12
0	3	3	4	11.27	5.84	32.14
0	3	3	5	0.00	0.00	38.41

Basic Simulation Results for Figure 5.24

a	t	b	WS Postion	% $B_{1,2}$	Indiviudal Workstation %Blocking	Indiviudal Workstation %Waiting
0	3	3	1	20.88	53.99	0.00
1	3	5	2	26.73	30.78	0.01
3	3	6	3	2.99	7.58	1.22
2	3	5	4	0.75	12.65	10.80
1	3	3	5	21.99	34.55	12.13
3	3	5	6	2.89	13.57	2.72
0	3	5	7	13.84	33.06	6.54
2	3	3	8	27.81	35.81	3.34
2	3	6	9	7.74	14.98	1.12
0	3	6	10	18.77	22.94	8.41
3	3	4	11	11.38	16.17	7.74
1	3	6	12	21.27	18.36	5.19
3	3	6	13	0.31	0.44	8.14
0	3	4	14	40.13	8.12	39.25
2	3	5	15	0.75	1.23	23.22
1	3	4	16	4.95	3.12	36.26
2	3	4	17	7.53	0.39	31.52
1	3	3	18	7.53	2.47	44.40
0	3	3	19	39.00	13.44	41.43
3	3	4	20	11.38	5.99	18.28
1	3	6	21		0.00	24.28

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